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TORONTO

LABORATORY EXPERIMENTS

IN

PRACTICAL PHYSICS

TO ACCOMPANY

THE REVISED EDITION OF

BLACK AND DAVIS' "PRACTICAL PHYSICS"

BY

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PREFACE

THIS book is a revision of the author's LABORATORY MANUAL IN PHYSICS, which was published ten years ago. The number of experiments has been increased from fifty to sixty-five. We did this not because we think that the average class should undertake more experiments in the school year, but in order to give teachers a greater choice of experiments so that they may adapt the work to their particular classes and to the needs of their environment. Each experiment has been carefully revised in the light of the experience and the suggestions which have been offered by teachers using the first edition.

Among the more important changes will be noted the *introductory paragraphs*. In these we try to show the relation of the experiment to other parts of the subject, and to make clear the significance of the experimental problem at hand. Toward this end we have pointed out some of the useful applications of the principles involved.

The exercises called "*Optional Experiments*," which appear after nearly every one of the regular experiments, offer to the student a field for the exercise of his initiative, and to the teacher an opportunity for greater elasticity in planning his course. They should be especially valuable as furnishing an incentive to the gifted student or to the student who shows particular aptitude and interest in the subject.

Experience has shown that much of the value of laboratory work is lost unless the exercise is followed by a review. We have therefore added groups of *questions* and *problems* of the sort which it is profitable to discuss with a class at the conclusion of an experiment.

Since careful illustrations are a great help to the student in getting a clear idea of the arrangement of the apparatus, we have increased the number of cuts. We have tried to grade the directions so as to put the student more and more on his own responsibility and initiative.

We feel sure that it is better for a class to undertake a comparatively small number of laboratory problems, say thirty or forty, and to do them thoroughly and to understand them, than it is to rush hurriedly through a much larger number and get only a very meager acquaintance with them. As an aid to some teachers in selecting the more fundamental experiments, we have starred (*) twenty-five which would probably be included in any first-year course.

Any book of this sort is largely a matter of compilation: selecting the material from various sources, trying it out, and then putting it into the form which experience has shown to be workable in the laboratory. In his task the author has particularly made use of the following books: *Ahrens, Hurley and Burns'* Practical Physics Manual, *Johnson and Earle's* Electrical Laboratory Tests, and *J. C. Packard's* Everyday Physics; also the Descriptive List of Elementary Exercises in Physics by *Edwin H. Hall,* Physical Laboratory Manual by *Chaffee and Saunders*, and Laboratory Experiments in Physics by *F. A. Waterman.* The author is greatly indebted to Dr. E. R. Schaeffer and to Mr. Bancroft Beatley both of Harvard University, to Mr. George A. Cowen of the West Roxbury High School (Boston), and to Mr. Arthur L. Jordan of the Polytechnic High School (San Francisco) for suggestions in preparing the manuscript.

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Note. In the above list of regular experiments twenty-five have been starred (*) as fundamental and should be included in any first-year course. After nearly every experiment there is outlined an *Optional Experiment*.

Reg. No. 21.

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H. S. Gautam

LABORATORY EXPERIMENTS IN PRACTICAL PHYSICS

INTRODUCTION

SUGGESTIONS TO TEACHERS

IT is now more than thirty years since we began to teach elementary physics in the laboratory. Every teacher of physics undoubtedly takes up the task of organizing his laboratory with great enthusiasm and high hopes. But sooner or later he finds that this business of teaching young people physics by means of laboratory exercises is a very difficult problem. No amount of costly apparatus or elaborate laboratory directions will produce that mental activity and curiosity about physical phenomena that we all want to stimulate in our students.

Preparing the way. Doubtless it would be the ideal method if each teacher made his own laboratory manual, and many have done so. This book is the result of one teacher's attempt to get together a set of experiments that represent a well-balanced course. The aim has been to make the directions so clear and concise that the average boy or girl who has in mind a general outline of the problem will not only be able to do the experiment but will catch the spirit of scientific investigation. It is assumed that when the class assembles for the laboratory exercise the teacher will first ask a few questions to make clear what the problem of the day is and how it is related to the previous work and to the practical affairs of life;

then he will *briefly* outline just how the problem is to be attacked in the laboratory. If the student has already mastered the written directions, he ought then to be able to proceed intelligently and expeditiously with the work in hand.

Recording the results. One reason why so much of our laboratory work in elementary physics is ineffective seems to be that the students get lost in the multitude of details and forget the point or purpose of the experiment. Sometimes the directions are given with such minuteness that the work is purely mechanical. This is reflected in the notebooks, which show no individuality and seem to indicate that the work has consisted merely in filling in certain blank spaces in a tabular form. It is, of course, expected that at first the student will need much help in arranging his notes in an orderly way; but these suggestions should become unnecessary as time goes on. The great danger in notebook work is artificiality. The student should write out his notes in his own words and in such form that when he reviews his work six months or a year later they will recall to his mind just what he did and what were his results.

Degree of accuracy. In the early days of student laboratory work a very large fraction of the time devoted to physics was spent in the laboratory. But in recent years we have come to believe that many subjects can best be presented in their *qualitative* aspects by the teacher in clean-cut classroom demonstrations, while the work of the student in the laboratory should be to perform a few well-selected experiments involving simple measurements. It is, of course, always to be remembered that this elementary work is not primarily physical *measurements*, but *physics*. Therefore it is hardly worth while at this stage of the work to spend much time in discussing percentage errors which are to be reckoned in tenths of one per cent. The engineer often has to be satisfied with results which check within five per cent. Why should we seek for such a high degree of accuracy as can only be attained by complicating the apparatus and the manipulation?

Laboratory examinations. So it has come about that the suggested apparatus is very simple and often of the commercial type. It is also suggested that the student do on an average only about one experiment per week. Frequent quizzes and reviews of the laboratory work have been found of great value. In this connection it is to be hoped that all the colleges will soon provide for a *practical laboratory examination* as a part of the admission examination in physics, and that the schools will introduce laboratory examinations as a part of the routine work to test the student's achievements in physics. This laboratory examination should not be simply a repetition of experiments already performed, but should also to some extent test the student's originality and power to apply the methods of the laboratory to new problems.

Correlation of laboratory work. Keen inspectors of the science work done in our secondary schools report that much of it fails because the laboratory work is not closely related to the recitations and class discussions and, what is still more important, to the needs and interests of the students. The laboratory problems should provide direct and obvious connections between what immediately precedes and follows. The student should go to the laboratory to find out by experiment some facts that are essential to the solution of a real physics problem. As far as possible these experiments should deal with the mechanisms and appliances of everyday experience. To aid the teacher in the selection of such practical experiments many optional experiments have been outlined which involve the use of commercial apparatus. Nevertheless, it must be borne in mind that the successful correlation of the laboratory work with the rest of the student's instruction and life depends not on books or apparatus but on the *teacher*.

SUGGESTIONS TO STUDENTS

Follow directions. Before beginning an experiment carefully read the directions through in order to have a clear idea of what you are going to do. Then read the directions again and follow closely each word because these directions have been carefully framed so as to prevent your wasting time and making needless mistakes. *Every word is significant.*

Check up your apparatus. You will notice that at the beginning of each experiment there is a list of the apparatus needed in that particular experiment. It will save time if you first run through the list and make sure that you have at hand on your table each article there specified, and that it is in good condition.

Errors of observation. All physical measurements are subject to accidental errors of observation, due to unknown causes, and therefore absolute accuracy can in no case be expected. The effect of such errors on the result can, however, be largely eliminated by taking the mean of several observations. But every observation should be made wholly uninfluenced by any previous observation or by an unconscious tendency to make all results agree.

Relative importance of observations. Although it is desirable that the final result of an experiment should have the greatest possible accuracy, yet this does not mean that every observation must be taken with the greatest care. Those observations which are liable to contain *the greatest percentage of error* will produce the greatest error in the final result, and must therefore be taken with the greatest care. The final result cannot be more accurate than the least accurate factor.

Laboratory notebook. Whatever the form of notebook used, it should contain a careful record of (*a*) what you actually do, (*b*) what you actually observe, and (*c*) what conclusions you draw from your own experimental facts.

(1) It is well to arrange your notebook in an orderly fashion. Begin each experiment on a new page and record first the date on which each experiment is performed as well as the number, title, and purpose of the experiment.

(2) Then put down all the measurements and facts which you have observed, recording each measurement as soon as you have made it, and *recording it just as you have made it* whether it seems to you at the time reasonable or not. The numbers thus recorded should not be the result of additions or subtractions done in the head. The original observations should never be trusted to loose sheets of paper, backs of envelopes, etc.

(3) Then compute the result which may reasonably be derived from the data at hand. In this arithmetical work arrange your computations in an orderly fashion so that it will be evident to anyone who examines the book just what your process has been. Be particularly careful not to crowd this work, to make very clear and legible figures, and to attach to each result its proper unit. Remember that decimal fractions are much more convenient to handle than common fractions, and that the use of logarithms and a slide rule will shorten the labor involved.

(4) It will be found that a carefully made diagram of the apparatus with descriptive labels attached will often be sufficient to show the method of carrying on the experiment. If this is not enough, add a few clear statements to show the method used.

(5) State the general conclusions which may be drawn from your experiment, and be careful to draw no conclusions which your facts do not warrant. In answering the questions suggested by the experiment, make complete sentences of such a sort that there is no trouble later in recalling the nature of each question.

Significant figures. A physical quantity should be recorded just as accurately as it has been measured. For example,

7.40 cm. in the record of an experiment does not mean exactly the same thing as 7.4 cm. The *first* record shows that the hundredths of a centimeter could be estimated, and that the length was estimated to be more nearly 7.40 cm. than 7.41 cm. or 7.39 cm. The *second* record means that the hundredths of a centimeter were not taken into account.

Suppose we find that three measurements of the same dimension give 12.55 cm., 12.58 cm., and 12.57 cm. In this case we are sure of the first three figures, 12.5, but the fourth figure was estimated and therefore is **doubtful**. To find the mean value we find the sum of these numbers, which is 37.70 cm., and then divide by 3. The mean value might be written 12.5666+ cm., but *this is wrong* because it assumes greater accuracy than the measurements warrant. We should keep *but one doubtful figure* in the mean value, that is, the first 6 and drop the rest; but since the next figure is 5 or more we call the doubtful figure one more. The mean value should be given as 12.57 cm.

Remember that the position of the decimal point has nothing whatever to do with the significance of figures. For example, the value accepted at present for the speed of light is 186,400 miles per second. The first three figures, 186, are sure, the 4 is doubtful, and the two ciphers serve to locate the decimal point. Again, the wave length of sodium light is 0.00005893 centimeters. The first five ciphers serve to locate the decimal point, the figures 589 are sure, and the 3 is doubtful.

Percentage of error. The actual error to be expected in a physical measurement may be large, as for example, 4 or 5 feet in measuring the velocity of sound; or it may be small, as for example, 1 or 2 thousandths of an inch in measuring the diameter of a wire. The difference between your experimental result and the accepted value (which has generally been obtained by a trained observer making a large number of trials with high-grade instruments) is called the *actual error*. But it is a much more significant expression of the degree of accuracy to find what fraction (expressed as percentage) this actual error is of

the accepted value. For example, suppose the velocity of sound under certain conditions is 1127 feet per second and your experimental result is 1132 feet per second. Then your actual error is 5 feet per second, which seems at first sight a big error. But the *per cent of error* is $\frac{5}{1127} \times 100$, or about 0.4%. *To find the per cent of error, divide the actual error by the accepted value, and multiply the quotient by 100.*

It is impossible to state a uniform rule for the degree of accuracy to be expected in the experiments in this book. The type of apparatus used and the conditions under which the experiment is performed must be considered. It is to be hoped that the results will not show an error of more than 1 per cent, but in certain experiments the errors may run to 5 per cent. Aim for the best results and try to improve in accuracy, but whatever you do, be honest with yourself in all your results.

Care of apparatus. Remember that the success of any experiment depends upon *two factors:* the form and accuracy of the *apparatus* and the skill of the *manipulator* in handling the apparatus. Every graduated instrument is more or less in error, but if you know the precision which you may reasonably expect to get from it and then work for that precision, you will be doing all that can be expected. Experience shows that students often blame the apparatus for their poor results when really the fault is due to their arithmetical mistakes in computation or their carelessness in the use of the apparatus. *Make each piece do its work to the limit.*

When your experiment is completed, be sure to leave your apparatus in good condition. Report to the instructor in charge anything which seems to be out of adjustment.

MECHANICS

EXPERIMENT 1

MEASUREMENT OF LENGTH

How accurately can you measure the sides of a right triangle?
How accurately can you measure the circumference and diameter of a circle?

Right triangle
30-centimeter rule or Bristol-board metric rule, 20 cm. long
Circular disk or brass weight
Strip of thin paper
Pin

Introduction. "The significance of measurements in our civilization and their effect upon everyday life may not be fully appreciated. From the beginning of life measurement is important. . . . Modern industry owes its efficiency largely to careful measurements . . ." * And so in the laboratory the student will learn to measure many different kinds of things, not mainly for the sake of the results he gets, but rather that all through life he may know a good measurement when he sees one, and may be able to discuss accurately and with confidence the quantitative problems that are always coming up.

The metric system is the one that is generally used in the laboratory and with a little practice we shall learn to use it with even more precision than our familiar English system. Its great advantage lies in the fact that, like our numbers, it is a decimal system and so is extremely easy to use. This experiment will serve as a brief review of the metric system and it is hoped that we shall learn to measure distances more accurately than heretofore. Nevertheless we shall find that all of our

* Circular of the U.S. Bureau of Standards No. 55, *Measurements for the Household.*

measurements are more or less inaccurate and it will be one of our tasks to determine how accurate each measurement is.

Directions. I. ***Right triangle.*** On a page in your notebook draw with a sharp hard lead pencil a right triangle with no two of its sides equal and with no side less than 10 centimeters in length. Make the corners clean and sharp. Label the triangle *ABC* as shown in figure 1, where *C* is the right angle.

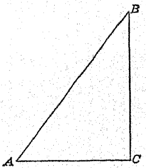


Fig. 1. Right triangle.

Measure each of the three sides with great care and record each length in centimeters and a decimal fraction of a centimeter. Note first the whole number of centimeters, then the number of millimeters, which are expressed as tenths of a centimeter (0.1 cm.), and lastly the tenths of a millimeter, which are to be estimated* and expressed as hundredths of a centimeter (0.01 cm.). *Always express a fraction as a decimal.* If it should happen that the end of a line exactly coincides with a millimeter mark on the rule, then record a zero in the hundredths place, thus, 12.30 cm.; and if it should happen that the end coincides with a centimeter mark on the rule, then record zeros in *both* the tenths and hundredths places, thus, 12.00 cm. This shows that we have tried to measure the length to a hundredth of a centimeter.

Record at once each measurement in your notebook (not on loose scraps of paper). It is well to arrange your record in tabular form as indicated below. Write nothing whatever in the laboratory manual.

Sides	Lengths
AB	— — . — — cm.
BC	— — . — — cm.
AC	— — . — — cm.

* It will be useful to remember that one half a millimeter is equal to 0.05 cm. and that 0.02 cm. is a little less than a quarter of a millimeter.

To check the accuracy of these measurements, let us apply the well-known Pythagorean theorem in geometry: *The square on the hypotenuse of a right triangle is equivalent to the sum of the squares on the two sides.* That is,

$$\overline{AB}^2 = \overline{AC} + \overline{BC}^2$$

Compute the length of the side AB from the above equation and compare the result with the length of the side AB as obtained by direct measurement. *How do you account for the discrepancy?*

Perform all your computations in your notebook and arrange this work in an orderly fashion. It is suggested that you show the results of your computations as follows:

$\overline{AC}^2$ = — — . — — cm.^{2}
$\overline{BC}^2$ = — — . — — cm.^{2}
$\overline{AC}^2 + \overline{BC}^2$ = — — . — — cm.^{2}
$AB = \sqrt{\overline{AC}^2 + \overline{BC}^2}$ = — — . — — cm. (By computation.)
AB = — — . — — cm. (By measurement.)
Difference = — — . — — cm.

II. ***Circle.*** Measure the diameter of a circular disk or brass weight with great care. Estimate to one hundredth of a centimeter (0.01 cm.). To measure the circumference of the cylinder, wrap tightly around it a strip of thin paper and prick a hole with a pin through the paper where it overlaps, as shown in figure 2. Measure carefully the distance between these two pinholes. Record your measurements thus:

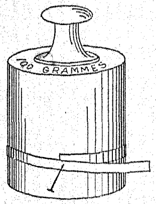


Fig. 2. Measuring the circumference of a cylinder.

Diameter = — — . — — cm.
Circumference = — — . — — cm.

To check the accuracy of these measurements let us apply another geometrical principle: *The number obtained by dividing the circumference of*

any circle by its diameter is approximately 3.14. This number is denoted by the Greek letter π (pronounced pī).

Compute the value of π from your values of the circumference and the diameter. Record the results thus:

$$\pi = \frac{\text{circumference}}{\text{diameter}} = \text{—} . \text{— —} \quad \text{(By experiment.)}$$

$$\text{True value of } \pi = 3.14. \quad \text{(By geometry.)}$$

$$\text{Difference or error} = \text{—} . \text{— —}$$

Optional experiment. Repeat the experiment on measuring the sides of a right triangle using a pair of dividers with sharp points and a diagonal scale. Figure 3 shows one end of a metric

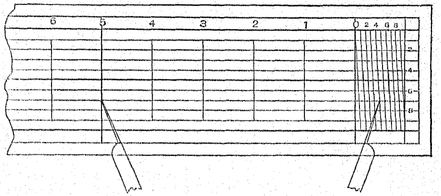


Fig. 3. Diagonal scale used to measure to 0.01 cm.

scale which is provided with a series of diagonal lines to assist in measuring to one tenth of a millimeter. Note that the first diagonal line, the one starting at the zero of the scale, forms a triangle with the vertical from the same point. The base of this triangle is one millimeter and the other horizontal lines cut by this diagonal increase gradually from 0.1 to 0.9 of a millimeter. Note that the diagonals are 1 millimeter apart.

Set the dividers exactly equal to the length of one side of the right triangle. To determine this distance, lay one point of the dividers on the zero point of the scale and find the number of whole centimeters to the other point along the top horizontal line. Then slide the dividers to the right along this line until one point is on the centimeter vertical mark and note the number of millimeters which are to be added. Finally slide the dividers down, keeping both points on the same horizontal line, and keeping one point

on the centimeter mark, until the other point just falls on an intersection of a horizontal line with a diagonal. Then the number of this horizontal line gives the tenths of a millimeter. For example, figure 5 indicates 5.47 centimeters.

QUESTIONS AND PROBLEMS

1. If you have made an error of 0.01 cm. in measuring the shorter side of the right triangle, what would be the error in your calculated value of the hypotenuse?

2. Suppose your error in measuring the diameter of your cylinder to be 0.01 cm. What would be the error in your computed value of π?

3. Suppose you made the same error (0.01 cm.) in measuring the circumference. What would be the error in the value of π?

4. Why is the computed error in problem 2 greater than that in problem 3?

5. How could you determine the error in the measurement of the circumference of the circle due to the thickness of the paper? Try it.

EXPERIMENT 2

DENSITY OF WOOD

What is the average weight in grams of one cubic centimeter of wood?

Rectangular block of wood, such as maple, oak, pine, or mahogany	30-cm. rule Platform or beam balance Set of weights

Introduction. Density means the weight per unit volume of a substance. Therefore we must get the weight and the volume of the sample block and then we can easily compute the weight of 1 cubic centimeter. Density is one of the important characteristics of materials. The engineer uses tables of densities in calculating the weights of bridges, buildings, and ships, which would be quite impossible to weigh *in toto*, and inconvenient to weigh in parts. What he does is to compute the volume from the dimensions, and then from his tables of densities in the

various engineering handbooks he can calculate the total weight of the structure.

Our problem is to find the density of a certain block of wood. Different kinds of wood have different densities. For example, poplar has a density of 0.39 grams per cubic centimeter, while lignum vitæ has a density of 1.33 grams per cubic centimeter.

The block of wood, although apparently rectangular, is not geometrically perfect, and therefore it will be necessary to make several measurements of its length, width, and thickness. Then we can compute the average, or mean, length, width, and thickness, and from these values determine the volume of the block. The weight can easily be found by using a platform, or beam, balance. Finally, we have to find the average weight in grams of 1 cubic centimeter of the wood.

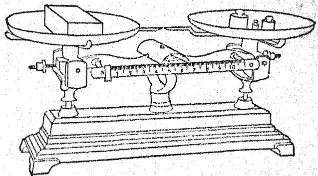


Fig. 4. Platform balance.

Directions. First adjust the balance (Fig. 4) so that it will just balance evenly with no load in either scalepan. A balance which quickly comes to rest is probably not in first-class condition. Therefore, we can judge better whether a balance is swinging evenly by noting the swings of the pans up and down, than by noting where it happens to come to rest.

Place a block of wood in the pan at the zero (left) end of the beam and counterbalance with weights. Steady the scalepan with the left hand while adding or removing the larger weights and so avoid jarring the balance and dulling the knife-edges. It will save time if you begin by using a weight which is probably a bit too heavy, and if so, removing it and replacing it with the next smaller weight. Continue in this way until you have the largest weight which is lighter than the object. Then

add the next smaller weight to the scalepan, and so on until within 10 grams of the weight. Make the final adjustment by using the slide along the beam. Take great care in counting up the weights used, and record this total weight (in grams and decimal fraction) at once in your notebook as the weight of the block.

To measure the block to a hundredth of a centimeter with an ordinary meter stick requires considerable care. The block should be placed on a sheet of white paper in a good light, and the measuring stick should be placed upon it so that one edge of the block is exactly in line with some centimeter mark, such as the 10-centimeter mark, as shown in figure 5. The other end of the block will probably not lie exactly in line with any millimeter mark on the scale, and so it is necessary to estimate the fraction of a millimeter. Express the result as centimeters and a decimal fraction thereof. For example, 12.35 cm.

To get the length, measure each of the four edges parallel to the grain of the wood. It is not likely that all these measurements, if carefully made to a hundredth of a centimeter, will give exactly the same result. But we can determine the average length by finding the sum of these four measurements of length and dividing by four.

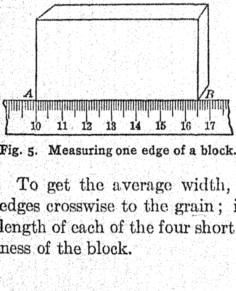


Fig. 5. Measuring one edge of a block.

LENGTH
12.35 cm.
12.37 cm.
12.33 cm.
12.38 cm.
4)49.43 cm.
12.357 cm.
Average length 12.36 cm.

To get the average width, measure each of the four long edges crosswise to the grain; in a similar manner measure the length of each of the four short edges and get the average thickness of the block.

It is very desirable to record all of these measurements in an orderly way, and so the following model is suggested:

Weight of block No. — = — — — . — g.

LENGTH	WIDTH	THICKNESS
— — . — — cm.	— — . — — cm.	— — . — — cm.
— — . — — cm.	— — . — — cm.	— — . — — cm.
— — . — — cm.	— — . — — cm.	— — . — — cm.
— — . — — cm.	— — . — — cm.	— — . — — cm.
4) — — — . — —	4) — — — . — —	4) — — — . — —
Average — — . — — cm.	Average — — . — — cm.	Average — — . — — cm.

Computation. The volume of a rectangular block is equal to the product of the length × the width × the thickness. In computing the volume of the block it will save time if we retain only **significant figures**, that is, if we retain in the average values for the length, width, and thickness only the first *doubtful figure*. Since the second-place decimal in these measurements was obtained by estimating to one tenth of a millimeter, this figure in each measurement is doubtful, and so, even in the average value, there will be some doubt about the second decimal place. It is customary if the next figure is 5 or more to discard it and to add one to the preceding digit, as shown in the illustrative example.

As a general rule, in multiplying numbers together, retain in the product only as many significant figures as there are in the least accurate factor.

In this case, the least accurate factor is the shortest side, which is the thickness, and so the final product should have no more figures than this measurement.

Record the results of your computation as follows:

Volume of block = — — cm³.
Density of —— wood = — — g./cm³.

More about significant figures. Since in each of the above measurements tenths of a millimeter, that is, hundredths of a centimeter, had to be estimated, it follows that each measure-

ment is uncertain to at least 0.01 of a centimeter. For example, suppose one edge of the block measured 12.46 centimeters; it would mean that we were certain of the first three digits, 12.4, but that the 6 was doubtful and probably somewhat in error. Again, suppose the width of the block measured 10.25 centimeters; this would mean that we were sure of 10.2, but were somewhat doubtful in regard to the final 5.

In each case we are dealing with numbers containing four significant figures, the last digit in each number being somewhat in doubt.

Now it is obvious that when we multiply these two dimensions together, the product will also be somewhat in error. Let us see how much.

12.46	127.7	654)465.7(0.712
10.25	5.12	4578
6230	2554	790
2492	1277	654
1246	6385	1360
127.7150	653.824	1308
		52

In the above computation the doubtful figures are printed in black type and it will be seen that in the product we would retain only four figures, that is, 127.7, saving only one doubtful figure.

If we suppose the thickness of the block to be 5.12 centimeters, then the volume, as shown above, would be 654 cubic centimeters. In this result we retain only three figures because the least accurate factor is the smallest dimension (the thickness), which has but three significant figures. We record 654 instead of 653 because the second doubtful figure, 8, was greater than one half, and therefore in discarding it we add one unit to the doubtful figure 3, making it 654 cm^3.

In the same way, when we divide two numbers which are obtained from measurements and so are more or less inaccurate,

we keep in the quotient only one doubtful figure. Thus, suppose the weight of the block to be 465.7 grams. To find the density we divide this weight by the volume just computed and the quotient is 0.712 grams per cubic centimeter. In this quotient we retain but three significant figures because the volume has but three significant figures, and the quotient can be no more accurate than the divisor or dividend, as shown above.

In general, then, all numbers obtained from measurements are more or less inaccurate, and so we may retain as significant figures only one doubtful digit. The result of any arithmetical computation can never be more accurate than its least accurate factor.

Optional experiment. Determine the density of a metal by measuring the length and diameter of a cylinder with a vernier caliper if available. The volume of a cylinder is equal to the area of base $\times$ height. That is,

$$V = \frac{\pi D^2}{4} \times H$$

where V is the volume, D the diameter, and H the height. Then weigh the cylinder as just described and compute the density (grams per cubic centimeter).

Vernier caliper. When using a meter stick it is necessary to *estimate* the tenths of millimeters, the smallest scale divisions. The vernier is a

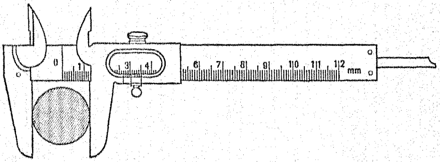


Fig. 6. Vernier caliper.

device which assists in the accurate reading of the fractional part of a scale division. The vernier caliper (Fig. 6) has two scales: one is fixed and the

other is arranged to slide along the fixed scale. In the metric instrument the fixed scale is divided into centimeters and millimeters and the sliding scale has 10 divisions which are equal to 9 millimeters. Therefore each division on the sliding scale is equal to 0.9 millimeters. When the jaws are in contact, the zero, or index, mark of the sliding scale coincides with the zero mark on the fixed scale; the first mark of the sliding scale falls short of a mark on the fixed scale by just 0.1 millimeters, and the second mark by 0.2 millimeters, etc. If the movable jaw is moved, say 0.4 millimeters from its zero position, the fourth vernier mark on the sliding scale coincides with a mark on the fixed scale. To read the metric vernier caliper, *note the left-hand division on the fixed scale nearest the vernier zero mark* (for example, 3.8 cm. in figure 7) *and the vernier division* (6 in this case) *which lies in the same straight line with some fixed scale division.* (The reading in this case is 3.86 cm.) That division on the slide scale which coincides with a division on the fixed scale gives the tenths of millimeters or *hundredths of centimeters.*

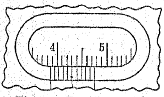


Fig. 7. Reading 3.86.

Many vernier calipers are made with two sets of jaws, one for outside measurements and the other for inside measurements. They are often provided with a double scale, one metric and the other English, reading to $\frac{1}{128}$ of an inch.

QUESTIONS AND PROBLEMS

1. How do you adjust a balance so that it swings evenly?

2. Why is it necessary to place the object to be weighed on the *left* scalepan, that is, the pan at the zero end of the scale beam?

3. In this experiment, which quantity is measured the more accurately, the volume or the weight? Give your reasons.

4. If white pine wood averages 27 pounds per cubic foot, compute the weight (pounds) of a plank 18 feet long, 1 foot wide, and 2 inches thick.

5. Calculate the weight of a concrete cylindrical tank which measures on the outside 10 feet high and 6 feet in diameter. Assume the thickness of the wall to be 4 inches and the density of concrete to be 150 pounds per cubic foot. (Don't forget the bottom of the tank.)

EXPERIMENT 3

THE STRAIGHT LEVER

How must the weights be arranged on a straight lever in order to balance?

Meter stick
Fulcrum or support for meter stick
Set of weights
Thread

Introduction. A crowbar is perhaps the most familiar example of a straight lever. The problem often arises how to use such a bar so that by applying a given effort (one's own weight) at one end a given load may be lifted at the other end. To solve such problems we must understand the **principle of moments.** The moment of a weight is its turning effect, which depends on its **weight** and its **distance** from the fulcrum. Thus,

Moment = weight × distance.

In this experiment we shall compare the moments of the weights tending to turn the lever in one direction with the moments of the weights tending to turn the lever in the opposite direction.

Directions. Suspend or support a meter stick at its midpoint, and if it does not quite balance, place a rider made of a

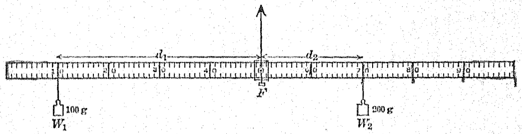


Fig. 8. Straight lever with unequal weights.

bent piece of sheet metal on the lighter side at such a point as to produce equilibrium. Hang by a thread a 100-gram weight W_1 at a distance of 40 centimeters d_1 to the left of the fulcrum F, and then hang a 200-gram weight W_2 at some point on the other side so as to balance it (Fig. 8). It is not necessary to

wait for the lever to come to rest; for it is in equilibrium when it swings through equal distances on opposite sides of the horizontal position. Record these weights W_1 and W_2 and their corresponding distances from the fulcrum as d_1 and d_2.

Repeat, using a different set of weights, and record both the weights and their distances from the fulcrum.

Then hang two weights W_2 and W_3 at different points on the same side of the fulcrum and balance them with a single weight W_1 on the other side. Record the weights and their distances from the fulcrum.

Arrange these data in some convenient tabular form such as the following:

TRIALS	W_1	d_1	W_2	d_2	W_3	d_3
1	100	40 cm	200	20		
2						
3						

Computation. Calculate the moment of each of these weights about the fulcrum as follows:

	$W_1 \times d_1$	$W_2 \times d_2$	$W_3 \times d_3$
Trial 1	— × — = —	— × — = —	
Trial 2	— × — = —	— × — = —	
Trial 3	— × — = —	— × — = —	— × — = —

Results. Answer the following questions in complete sentences.

(*a*) *What relation seems to exist between the moment of the weight on the right and that on the left of the fulcrum? Compare* $W_1 \times d_1$ *and* $W_2 \times d_2$.

(*b*) *Are the differences between the moments on either side of the fulcrum greater than would be expected from the experimental errors?*

(*c*) *How does the sum of the moments on the right of the fulcrum compare with the sum of those on the left?*

Optional experiment. Suspend the meter stick from a spring balance attached at the fulcrum F and determine first the weight of the lever and then the upward pull exerted by the fulcrum when the lever is loaded with two or more weights which are in equilibrium. *Compare the amount of the upward force exerted at the fulcrum with the sum of the weights including the weight of the lever.*

Suspend any convenient object, like a jackknife, screw driver, or monkey wrench, whose weight is not known, on one side of the lever and balance it with a known weight on the other side.

Compute the weight of the object by the principle of moments, which has just been illustrated. To check this result, weigh the object on the ordinary scales and compare results.

QUESTIONS AND PROBLEMS

1. A pair of metal-cutting shears is used to cut a wire. A force of 20 pounds is applied 9 inches from the pivot. How much force is exerted on a wire which is placed 1.5 inches from the pivot?

2. A man weighing 150 pounds wants to pry up a rock weighing 600 pounds by exerting his entire weight on the end of a 5-foot crowbar. Where must the fulcrum be placed? Neglect the weight of the crowbar.

3. A seesaw plank is set up so that it just balances on its fulcrum. A boy weighing 100 pounds sits 6 feet on one side of the fulcrum; a girl weighing 80 pounds sits 6 feet on the other side of the fulcrum. How far from the fulcrum must a second girl weighing 60 pounds be placed to balance the plank?

4. To determine the combined turning effect of two or more weights acting at different positions but on the same side of the fulcrum, would you add the weights or their moments? Why?

5. What is the condition of moments which must exist when a lever just balances? This is called the **principle of moments.**

EXPERIMENT 4

WEIGHT OF A LEVER AND ITS CENTER OF GRAVITY

Where may the weight of a lever be considered to act?

Meter stick loaded at one end	Set of weights
Triangular block of wood	Thread

Introduction. In experiment 3 we did not have to consider the effect of the weight of the lever itself because the lever was uniform and was balanced in the middle. In practical work the weight of the lever itself has to be considered, and our problem now is to find out how to make allowance for the weight of the lever. For example, suppose a man lifts 10 pounds of coal on a shovel which weighs 6 pounds (Fig. 9). His left hand is at the end of the shovel and his right hand is supposed to be halfway between the end of the shovel and the coal. We may consider his right hand as a fulcrum. It is evident that part of the weight of the shovel tends to turn it down on the right side and that the rest of the weight of the shovel tends to turn it down on the left side. It would be very convenient if we could find one point at which we could consider the whole weight to be concentrated, that is, as if the lever weighed nothing and as if we had another weight at this point.

Fig. 9. A useful form of lever.

Directions. Let us consider the loaded meter stick AL (Fig. 10) as an example of a non-uniform lever whose weight cannot be neglected. Hang a known weight W at some fixed point B, and then slide the meter stick along the triangular block of wood F until the whole thing just balances. Then the moment of W about F is equal to $W \times BF$.

Let us call the center of weight, if there be one, X, and its

distance from the fulcrum FX; then its moment is equal to the *weight of the lever* $\times$ FX. But this moment is equal to the moment on the other side $W \times BF$. In other words we have

$$Wt.\ of\ lever \times FX = W \times BF.$$

If we know the weight of the lever, we can compute the value FX and determine the position of X on the meter stick.

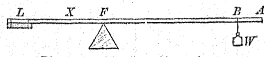


Fig. 10. A non-uniform lever.

First weigh the loaded meter stick to the nearest tenth of a gram. Then attach by a thread a 100-gram weight W to the meter stick at B, 10 centimeters from the end A, and balance the whole thing on the block F as a fulcrum. Note the distance AF of the fulcrum from the end of the meter stick.

Repeat this experiment several times with different known weights at various positions, but each time determining the distance AF.

Computation. First, find the distance of the known weight W from the fulcrum F, that is, BF. From this calculate the moment of W about F, that is, find the product $W \times BF$. Then, knowing the weight of the lever, we may calculate its acting distance FX from the fulcrum. That is,

$$FX = \frac{W \times BF}{Wt.\ of\ lever}.$$

From this we can find the position of X on the meter stick, that is, the distance AX.

Compare the various positions of X, the center of weight, as determined in the several trials.

Finally, balance on the block F the lever alone without W. This position of F, where the lever balances on a knife-edge, is called its *center of gravity*. Note the distance of this center of gravity from the end A of the meter stick.

It will be well to arrange the data and computations in tabular form somewhat as follows:

Weight of the loaded lever — g.

Data			Computations			
W	AB	AF	BF	$BF \times W$	$FX = \dfrac{BF \times W}{Wt.\ of\ lever}$	AX
100 g.	10.0 cm.					
200 g.	10.0 cm.					
200 g.	15.0 cm.					
500 g.						

Center of gravity (CG) is located —— cm. from A.

Results. (1) *Does the weight of the lever act as if collected at one point?*

(2) *Does the weight of the lever act as if concentrated at the center of gravity?*

Optional experiment. Applying the results of this experiment, find the weight of the lever by balancing it against a known weight. Compare this computed weight with the actual weight as determined by the platform scales.

Also apply the results of this experiment to find the weight of an iron ball by balancing it against the known weight of a lever. Compare this computed weight with the actual weight as determined by the platform scales. Draw carefully labeled diagrams showing dimensions.

QUESTIONS AND PROBLEMS

1. Where is the center of gravity of a uniform bar?

2. If you know the weight and center of gravity of a meter stick loaded at one end, how could you compute the weight of the load? Assume the meter stick to be uniform.

3. A boy who weighs 60 pounds uses as a seesaw a 15-foot plank which weighs 70 pounds and which has its center of gravity in the middle. If he

sits 1 foot from one end, how far from this same end must the fulcrum be placed in order to balance?

4. A uniform bar weighs 8 pounds and is 10 feet long. It balances 3 feet from one end when 12 pounds is hung from this end and an unknown weight from the other. How heavy is the unknown weight?

5. A uniform plank 20 feet long, weighing 200 pounds, rests on a flat roof with 8 feet of its length projecting beyond the edge of the roof. If a keg of nails weighing 50 pounds rests over a point 1 foot from the inner end, how far out on the plank beyond the edge of the roof may a man weighing 180 pounds go without tipping the plank?

EXPERIMENT 5

PARALLEL FORCES

What two conditions must always exist to have parallel forces in equilibrium?

2 Spring balances (2000 g.)	Meter stick
Set of weights	Fish line

Introduction. When an automobile moves across a bridge (Fig. 11), how is its weight distributed on the two supports at the ends of the bridge? When two men carry a heavy weight on a stick between them, how does the upward pull exerted by each man depend on the position of the weight? If two men stand on a horizontal ladder which is supported by a block and tackle attached near each end of the ladder, how much does each block have to support?

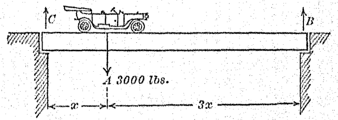


Fig. 11. Parallel forces acting on a bridge.

We may study such problems by suspending a meter stick in a horizontal position and then attaching one or more weights at various points along the stick. In each case we shall (1) com-

pare the sum of the forces acting in one direction with the sum of the forces acting in the opposite direction, and (2) compare the sum of the moments of the forces tending to produce clockwise rotation with the sum of the moments of the forces tending to produce counter-clockwise rotation.

Directions. Hang two spring balances F_1 and F_2 from some convenient support * and suspend a meter stick from the hooks of the balances, as shown in figure 12. Read and record the forces required to support the stick alone.

Suspend the weight W from the sliding loop B and make the distance BC equal to 25 centimeters. Read each balance and from its reading subtract the amount which it read with the meter stick alone. Record these results as the forces F_1 and F_2.

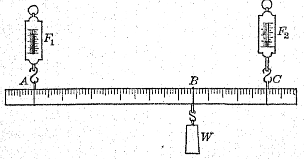


Fig. 12. Meter stick with three parallel forces.

In the same way find the upward forces when the weight W is placed 40 centimeters from C and again when 50 centimeters.

Finally hang two weights from the stick and determine the upward forces needed to support them.

Make a simple diagram in each case, indicating the distances on the meter stick by dimension lines and representing the forces by arrows drawn to a scale which will be specified by the instructor. Also note the amount of each force at the right of the arrow representing it.

Computation. Compute in each case the sum of the upward forces and compare with the downward force or forces (weights).

Compute the moment of each force about A and find in each case the sum of the moments tending to produce clockwise

* In case there is no convenient support for the balances, the experiment may be done by using 4 spring balances and arranging the apparatus flat on the table with clamps to hold the balances.

rotation and the sum of the moments tending to produce counter-clockwise rotation.

Repeat the computations in one case, using some other point, such as C, as the axis of rotation.

Results. When several parallel forces are in equilibrium, (1) *how does the sum of the forces acting in one direction compare with the sum of the forces acting in the opposite direction?*

(2) *How does the sum of the moments of the forces tending to produce clockwise rotation about any given point compare with the sum of the moments of the forces tending to produce counter-clockwise rotation about the same point?*

Optional experiment. When two equal parallel forces acting in opposite directions are applied to a body at points some distance apart, they tend to make the body rotate. Such a pair of forces constitutes a **couple.** No single force can balance a couple, but a second couple can do so, if it tends to make the body rotate in the opposite direction.

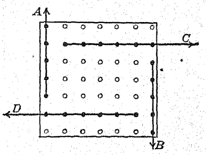


Fig. 13. Four forces at right angles.

We may study the conditions of equilibrium of couples by placing a square board on bicycle balls and then by applying forces A, B, C, and D to inserted pegs, as shown in figure 13. Vary the tension on the balances until the forces act along the cross-lines of the board. Notice that force $A = B$ and force $C = D$. Record the forces, their points of application, and directions on a diagram. Take some peg as the turning-point and compute the sum of the moments clockwise and also the sum of the moments counter-clockwise about this point. Compare these sums. Repeat the computation using some other peg as the turning-point.

Try another case with the pegs in different positions.

QUESTIONS AND PROBLEMS

1. Is the sum of the forces acting in one direction in this experiment *absolutely* equal or only *approximately* equal to the sum of the forces acting in the other direction? Explain.

2. Suppose you made a mistake of 10 grams in measuring one force. How much error will this cause in its moment?

3. Where must the load be placed on a 5-foot stick so that a boy at one end will carry one fourth of the load?

4. A steam roller weighing 10 tons has gone one fifth the length of a bridge-span. How much of the weight is borne by each end of the span?

5. A 12-foot ladder is used as a staging by two painters. The ladder is supported by two ropes attached at the ends. The weight of the ladder is 50 pounds and the center of gravity is 5 feet from the foot. One of the painters weighs 140 pounds and stands 2 feet from the foot of the ladder, and the other painter weighs 160 pounds and sits 2 feet from the other end. How much does each rope hold up?

EXPERIMENT 6

INCLINED PLANE

How much work is required to pull a loaded car up an inclined plane?

Smooth board about 100 cm. long	Spring balance (2000 g.)
Support for one end	Set of weights or other load
Car (Hall's) with cord attached	Meter stick

Introduction. Everyone is familiar with the fact that it is easier to roll a barrel of flour up an inclined plane from the sidewalk into a truck than it is to lift the barrel straight up. But how about the amount of work done? Technically work means the overcoming of resistance. A barrel of flour resists being lifted because it is attracted by the earth. We can measure the work done in lifting the barrel straight up by multiplying the weight W by the height H. For example, 200 pounds lifted 3 feet would require 200×3, or 600 foot-pounds of work. But when the barrel is rolled up a plank, the force required is less and the distance is greater. The work done is the product of this force F times the length of the inclined plane L. We wish to compare the amounts of work in each case, that is, the two products $W \times H$ and $F \times L$.

Directions. In this experiment we shall pull a loaded car up a board placed in a slanting position. We may use a spring balance* to measure the force F required to draw the car up the incline. The weight of the car and its load is the weight W which is lifted. To measure the slope of the board, lay off some convenient distance L along the board and measure its corresponding height H, as shown in figure 14. It should be noted that it will be more convenient to use the *lower* side of the inclined board in measuring *both* the length and height.

Several precautions should be observed. First, note the zero point of the spring balance for the slant used and make

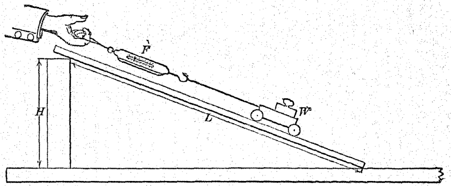


Fig. 14. Pulling a loaded car up an incline.

the necessary corrections, if appreciable, in its readings. Second, determine whether friction plays a large part in the effort required to pull the car up the incline. Evidently this effort will be a little more than if friction could be entirely eliminated. But if the car is allowed slowly to roll down the incline, the effort required to hold it back will be slightly less because of the friction. One half the difference between these two pulls is the force required to overcome friction. If this friction is very small, it may be disregarded.

First set the board up so that its angle of slope is approxi-

*Sometimes it is more convenient to perform this experiment by using instead of the spring balance a fixed pulley at the upper end of the incline and hanging on weights enough to pull the car up the grade.

mately 30° and measure with a meter stick to tenths of centimeters the length and height of the inclined plane. Determine with a spring balance the force parallel to the plane required to haul the loaded car slowly and steadily up the plane. Make, if necessary, allowance for the error in the zero point of the balance and for the friction of the car.

Then set the board at an angle of about 45° and repeat all observations. Repeat the experiment with different loads in the car.

Tabulate your data and results somewhat as follows:

Data					Results	
Trial	Weight W	Effort F	Length L	Height H	Work done $W \times H$	Work put $F \times L$
1	g.	g.	cm.	cm.	g.cm.	g.cm.
2						
3						
4						

Results. Compare in each trial *work accomplished* in lifting the car and its load straight up ($W \times H$) with *work expended* in pulling the car up the incline ($F \times L$), assuming that friction has been eliminated.

Compare in each trial the *mechanical advantage*, that is, the ratio of weight lifted to effort applied $\left(\frac{W}{F}\right)$ with the *velocity ratio*, that is, the ratio of the distance which the effort moves to the corresponding distance which the weight is lifted $\left(\frac{L}{H}\right)$.

Optional experiment. Find the work expended (neglect friction) in drawing a loaded car up an incline by a force acting *parallel to the base* of the incline. If we let the string attached to the car pass through a slot cut in the plane, we can easily measure the horizontal force needed to draw the car up the incline. The work expended equals the product

of this force times some horizontal distance; the work accomplished is equal to the weight lifted times the corresponding vertical distance. Compare these products.

QUESTIONS AND PROBLEMS

1. What is gained in making the slope of an incline less steep?

2. What is lost in making the slope of an incline less steep?

3. How much work (foot-pounds) is done in raising a ton of coal 1500 feet from the bottom of a mine?

4. What weight can be moved up an incline which rises 1 foot in 25 feet along the incline by a pull of 200 pounds? Assume that friction is negligible.

5. What force will be required to push an automobile weighing 2 tons up a grade which rises 5 feet for every 100 feet of length, friction being neglected?

EXPERIMENT 7

SLIDING FRICTION

How does starting friction compare with sliding friction?
How much is the coefficient of sliding friction for leather on wood?

Board having a smooth surface	Set of weights
Wooden box with pieces of leather glued to the bottom *	Spring balance (2000 g.)
	Meter stick

Introduction. The fan on an automobile is driven from the crankshaft by means of a leather or canvas belt. The effectiveness of this method of transmitting power to the fan depends on the friction between the belt and pulleys. In the same way the usefulness of the brakes on an automobile depends on friction between the brake lining and the steel drum. In fact, the automobile could not propel itself along the road except for the friction between the tires on the driving (rear) wheels and the road.

* This method of performing the experiment was suggested by Mr. Frank M. Gilley of the High School at Chelsea, Mass.

On the other hand it is one of the great problems of the mechanical engineer to eliminate or reduce to a minimum friction in machines. This is because friction reduces the efficiency of a machine since some work must be done against friction and this is usually wasted as heat, and besides the friction causes much wear on the rubbing surfaces.

By friction we mean the resistance encountered when we attempt to slide one surface over another. The force necessary to overcome friction depends upon so many conditions, such as the materials, the nature of the surfaces, the lubrication, and the pressure between them, that it is very difficult to make any general or exact statements about friction. However, in this experiment we shall be able to compare the force needed to start a body sliding on a horizontal surface with that required to keep it sliding, and to determine the ratio between the force required to keep a body sliding and the perpendicular force holding the surfaces in contact, that is, the *coefficient of sliding friction.*

Directions. I. ***On a horizontal plane.*** Find the weight of the wooden box by means of a spring balance. Place the board

Fig. 15. Measuring sliding friction.

on the table and set the friction box upon it. By means of a cord attach the hook of the balance to the screw eye in the end of the box (Fig. 15). Holding the spring balance horizontally, find how many grams' pull is required to start the box sliding and how much to keep it moving slowly and steadily along the board. The box will stick a little in places where the friction is greatest, and so several trials should be made and the average taken as the friction resistance. It is easier to read the balance if the board is drawn under the box than if the box is pulled over the board.

By loading the box with weights we may get any desired pressure between the bearing surfaces. We may well start with as low a pressure as will give a fairly steady reading on the spring balance. Then increase the load and make five trials, using widely varying loads up to the capacity of the balance. Compute in each trial the coefficient of sliding friction expressed as a decimal and then the average coefficient of sliding friction for leather on wood.

Record the data and results in tabular form:

Trials	I	II	III	IV	V
Weight of empty box .					
Load					
Weight of box and load					
Starting friction . . .					
Sliding friction . . .					
Coefficient of sliding friction					

II. *On an inclined plane.* Raise one end of the board until the loaded box, once started, will slide slowly down the board with a uniform velocity. Then, keeping the board in this position, measure the vertical distance H from the under side of the raised end to the table and the horizontal distance B from the foot of this vertical line to the point where the lower end of the board rests on the table (Fig. 16).

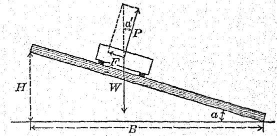


Fig. 16. Friction on an incline.

Change the weights in the box and in each trial adjust the height so that the box will just continue to slide after it is once started by the hand.

In each trial compute the ratio of the vertical distance to the horizontal and express the result as a decimal fraction. Record the data and computed results as follows:

	Vertical Distance (H)	Horizontal Distance (B)	H/B
Box lightly loaded	cm.	cm.	
Box with added weight . . .			
Box heavily loaded			

Conclusions. Answer the following questions in complete sentences.

Is the starting friction in each trial greater than the sliding friction?

Does the sliding friction increase with the pressure?

Does the coefficient of sliding friction increase with the pressure?

Does the numerical value obtained by dividing the vertical distance by the horizontal approximately equal the coefficient of sliding friction? *

Optional experiment. Arrange a box with three pieces of an automobile tire attached to the bottom to serve as runners. Then measure with a suitable spring balance the force necessary to drag the box loaded with rocks along a road. Determine the coefficient of starting friction and the coefficient of sliding friction on various road surfaces.

QUESTIONS AND PROBLEMS

1. Why is it so difficult to obtain consistent experimental results in friction experiments?

2. Why is the term *coefficient* used for the value of the ratio of force of friction to the total normal pressure?

3. What does your ordinary experience with shoes teach you as to the

* For the geometrical proof of this conclusion, study page 137 in the revised edition of Black and Davis' *Practical Physics.*

coefficient of friction between leather and wood and that between rubber and wood?

4. The tractive effort (draw-bar pull) of a locomotive does not exceed the weight on the drivers times the coefficient of adhesion, which is usually taken as 0.25. Is this coefficient the same as the coefficient of starting friction or of sliding friction?

5. A locomotive weighing 200 tons has a coefficient of adhesion of 0.235. What is its tractive effort?

EXPERIMENT 8

EFFICIENCY OF A COMMERCIAL BLOCK AND TACKLE

What fraction of the work put into a commercial block and tackle is got out with various loads?

Two double pulleys (commercial form, yacht size)	Weights (10 to 50 lbs.)
	Spring balance (20 lbs.)
Rope	Meter stick

Introduction. In any commercial machine the work done by the machine in lifting a weight or overcoming a resistance is always less than the work expended on or put into the machine. To be efficient a machine must return as useful work a large part of the work applied to it. The mechanical efficiency of a machine is the ratio of the output to its input. It is always less than one, and is usually expressed as a percentage. Thus,

$$\text{Efficiency} = \frac{\text{output}}{\text{input}} = \frac{\text{work done by machine}}{\text{work done on machine}},$$

or $$\text{Output} = \text{efficiency} \times \text{input}.$$

One of the simplest machines to use to illustrate the meaning of efficiency is the commercial block and tackle, which consists of a combination of pulleys connected by a rope. One block, called the *fixed* block, is fastened to a hook in the ceiling or to a bracket on the wall and the other block, known as the *movable* block, is attached to the load to be lifted. It will be noted that the movable block is the one that moves with the weight.

We shall find it helpful to compute the **velocity ratio** of the block and tackle, which is the ratio obtained by dividing the distance through which the driving force (effort) acts by the distance through which the resisting force (load) acts in the same time. We can easily compute this velocity ratio by counting the number of supporting strands. For example, in the apparatus shown in figure 17 there are four strands supporting the movable pulley and so the velocity ratio is four. This means that to raise the weight 1 foot the effort acts through a distance of 4 feet.

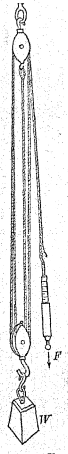


Fig. 17. Two double blocks.

Directions. Attach one block to a ring in the ceiling or to a suitable bracket from the wall and hang a weight W on the lower block. Determine by means of a spring balance the effort F required to raise the load slowly and steadily. Note the zero error of the spring balance when used in this position and make the proper correction for this zero error.

Determine by actual measurement the distance through which the effort must be exerted in order to lift the weight 1 foot. Compare this value of the velocity ratio with that which you would expect from the arrangement of ropes and pulleys.

Make several trials, using weights of 10, 20, 30, and 50 pounds.

Computations. The work done by the effort, that is, the input, is equal to the effort times the effort distance. The useful work done on the load, that is, the output, is equal to the load times the distance the load is lifted. It is to be noted that the useful output means the work done in lifting the load exclusive of the weight of the movable block. Assuming the load is raised 1 foot, calculate output and input in each trial. Finally compute the efficiency, that is, the ratio of output to

input, of the block and tackle at the different loads and express this efficiency as per cent.

It will be convenient to record the data and computed results of this experiment in tabular form somewhat as follows:

Load in Pounds	Effort in Pounds	Velocity Ratio	Output in Foot-pounds	Input in Foot-pounds	Efficiency in Per Cent
10		4			
20		4			
30		4			
40		4			
50		4			

Results. If time permits, it will be interesting to plot the results of this experiment as two curves showing graphically the relation of the *driving effort* to the *load* and the relation of the *efficiency* to the *load.* It is customary to plot the loads along the "x," or horizontal, axis and the efforts and efficiencies along the "y," or vertical, axis.*

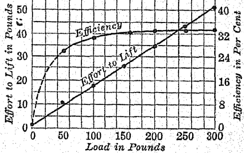


Fig. 18. Curves of a differential chain block.

Figure 18 shows a graph which is typical for many machines. It will be noticed that the effort-load curve starts a little above zero, as some effort is required to drive the machine unloaded. The efficiency curve always starts at zero, since the efficiency at no load must necessarily be zero.

(1) *How does the effort applied to a commercial block and tackle vary with the load?*

(2) *Is the efficiency of a block and tackle the same with different loads?*

(3) *What becomes of the "wasted work"?*

* For further information in regard to plotting curves see Appendix.

Optional experiment. Measure the velocity ratio and the efficiency under different loads of a differential chain block (quarter-ton capacity). For further details about its construction and operation see section 34 in the revised edition of Black and Davis' *Practical Physics.*

QUESTIONS AND PROBLEMS

1. State a general law of machines involving *effort, efficiency, load,* and *velocity ratio.*

2. Show by a sketch how you would arrange fixed and movable blocks so that an effort of 150 pounds would support a load of 450 pounds. Neglect the weight of the movable block.

3. Assuming that a given block and tackle has an efficiency of 65 per cent and each block has two sheaves, compute the weight which three men whose combined weight is 500 pounds could hoist.

4. A block and tackle consisting of a double fixed block and a single movable block is used to lift a stone weighing 500 pounds. The effort required is 215 pounds. Compute the efficiency of the block and tackle.

5. The efficiency of a set of pulleys consisting of a triple fixed block and a triple movable block is 70 per cent. What force is needed to lift a load of one ton?

EXPERIMENT 9

AN AUTOMOBILE JACKSCREW

What is the velocity ratio and what is the efficiency of an automobile jackscrew under varying loads?

Ford jackscrew
An 8-foot lever arm capable of sustaining a ton load
Anchorage bar
Three 50-pound iron weights and hanger
Spring balance (20 lbs.)
Yardstick

Introduction. Jackscrews have long been used by builders to raise buildings from their foundations. A small force applied to the end of an iron bar which is used to turn the screw causes the screw to exert an enormous upward force through a very short distance. In one complete revolution of the handle the

load is lifted the distance between two adjacent threads (*pitch of the screw*). The extensive use of automobiles has made many people acquainted with the automobile jackscrew, which is merely a modification of the older builders' jackscrew. In this newer form, the effort is applied to the handle up and down and is then transmitted through a bevel gear to a nut, which turns and lifts the screw.

In order to get a sufficient load to test the jackscrew under conditions which approach actual working conditions, the jack is placed under a long lever a short distance from the fulcrum, as shown in figure 19. By this arrangement the total load to be lifted is considerable and can readily be computed from the

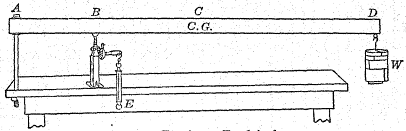


Fig. 19. Testing a Ford jackscrew.

principle of moments. Consider the effect of the weight of the lever which acts at its center of gravity and of the weight W, which is suspended at the opposite end from the fulcrum. Then compute the sum of the moments about A tending to turn the lever clockwise, and make this equal to the moment of the upward push of the jackscrew against the beam.

The velocity ratio can be computed from the circumference of the circle through which the effort moves and from the distance the load is lifted, that is, the pitch of the screw. Both distances must be expressed in the same unit.

The efficiency of the jackscrew can be obtained by computing the output, that is, the work done in lifting the total load on the screw a unit distance, say 1 foot, and the input, or the work done by the effort required to lift this load 1 foot. The output in foot-pounds is then equal numerically to the load expressed

in pounds, and the input in foot-pounds is equal to the effort times the velocity ratio. The efficiency is equal to the output divided by the input, and the decimal fraction is expressed as per cent.

Directions. First weigh the beam and find the position of its center of gravity by balancing it on a knife-edge. Then set up the apparatus as shown in figure 19, and level the beam by means of the screw at *A*. Suspend a 50-pound weight at *D*. Measure the effort with a 20-pound spring balance *E* attached to the end of the handle. Read the balance when it is acting at right angles to the handle and moving slowly.

Then increase the suspended weight by 50 pounds and measure the effort.

Finally, move the jackscrew up nearer to the end *A*, thus increasing its load, and repeat the experiment.

Measure the pitch of the screw by counting the number of threads in a given distance, and then compute the distance between two successive threads. Measure the length of the handle from the center of its pivot to the point where the balance is attached. This distance is the radius of the circle through which the effort moves.

Computation. Calculate the total load resting on the jackscrew in each case.

Compute the output (foot-pounds) in each case, assuming that the load is raised 1 foot.

Compute the circumference of the circle through which the effort acts and divide this circumference by the pitch of the screw to get the velocity ratio.

Then the input will be equal to the effort times the velocity ratio.

Finally, the efficiency is computed in each case as the ratio of the output to the input and expressed as per cent.

Results. The results of this experiment may well be expressed graphically by plotting two curves, one to show the relation of the effort to the load and the other to show the re-

lation of the efficiency to the load. It is customary to plot the loads horizontally and the efforts and efficiencies vertically.

Optional experiment. An office stool or a piano stool which is arranged to screw up and down may be used instead of an automobile jackscrew. Place a heavy load, such as a hundred-pound weight, on the top of the stool. Measure the force required to raise the weight slowly and steadily by pulling on a spring balance and revolving the top as the cord unwinds from the rim, as shown in figure 20. Make several trials, using widely varying weights, and compute the efficiency in each case.

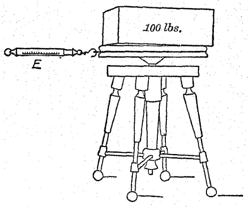


Fig. 20. Testing a piano stool.

QUESTIONS AND PROBLEMS

1. State a general law concerning the jackscrew involving the *effort*, *load*, *pitch*, *circumference of the circle* through which the effort moves, and the *efficiency*.

2. State the same law involving the *velocity ratio*.

3. Of what advantage is the large amount of friction found in a jackscrew?

4. How could the efficiency of a jackscrew be increased?

5. How could its velocity ratio be increased?

6. If the screw on a bench vise has 9 threads to an inch and if the effective lever arm of the handle is 6 inches, what is the velocity ratio?

7. Assuming that two thirds of the work put into the vise in the preceding problem is used to overcome friction, what is the clamping force exerted by the jaws when 20 pounds is applied to the handle?

EXPERIMENT 10

BUOYANCY OF LIQUIDS — ARCHIMEDES' PRINCIPLE

I. *How much does a body lose in apparent weight when entirely immersed in a liquid?*

II. *How much liquid does a floating body displace?*

Solids denser than water (150–250 g.), such as stone, coal, glass, block of lignum vitæ, etc.
Platform balance with weights and support, or a spring balance (250 g.)*
Overflow can
Catch bucket or beaker with wire loop for suspension
Solids less dense than water, such as blocks of wood, apples, etc.
Jar of water and thread

Introduction. It is common experience that one can lift a much larger stone to the surface of water than one can lift out of the water. The anchor of a boat seems to be much heavier when it is out of water than when it is in water. A submarine boat may float partly submerged or sink to any depth, as conditions may require. What is it that determines whether a thing sinks or floats in a liquid?

It is obvious that any object when submerged displaces a *volume* of liquid equal to the *volume* of the object itself. It will be interesting to compare the *weight* of the liquid displaced with the loss of weight of a body either partly or wholly submerged in a liquid.

This buoyant action of water was probably first studied about 240 B.C. by Archimedes, and therefore the principle involved is known as Archimedes' principle.

Directions. I. ***Solids that sink.*** First weigh the specimen, such as a piece of stone, *in air* and then when entirely

* If a spring balance is used in this experiment, each of the weights will be in error by 1 or 2 grams, and consequently the results will not agree precisely with the principle involved.

immersed in water in a jar. Compute the loss in apparent weight.

To determine the weight of the liquid displaced, a can with a spout, called an overflow can (Fig. 21), is filled until the water runs out at the spout. Then by placing a weighed catch bucket under the spout and carefully lowering the piece of rock into the overflow can, the water which is displaced overflows into the bucket and may be caught and weighed.

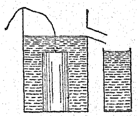


Fig. 21. A heavy solid.

If time permits, repeat the experiment, using gasoline as the liquid instead of water.

Record your observations and results as follows:

Liquids Used	Water	Gasoline
Weight of solid in air	g.	g.
Weight of solid in liquid	g.	g.
Loss of weight in liquid	g.	g.
Weight of catch bucket, empty	g.	g.
Weight of catch bucket and liquid displaced .	g.	g.
Weight of liquid displaced	g.	g.

Compare the loss of weight of the stone in a liquid with the weight of liquid displaced.

II. ***Solids that float.*** A solid which is lighter than water loses its entire weight and therefore we should expect it to sink into the water until it displaced its own weight of water. To find out how the weight of a floating body compares with the weight of the liquid displaced by it, first weigh the object, such as a block of wood or an apple; then arrange the overflow can and catch bucket as shown in figure 22, and determine the weight of water displaced by the floating object.

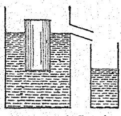


Fig. 22. A floating solid.

Record these observations and results as follows:

Weight of solid	g.
Weight of catch bucket, empty	g.
Weight of catch bucket and water displaced .	g.
Weight of water displaced	g.

If time permits, repeat the experiment using gasoline as the liquid instead of water.

Compare the weight of a floating object with the weight of the liquid displaced by it.

Optional experiments. A more convenient method of measuring the volume of liquid displaced by an object that sinks is to fill a graduated glass cylinder partly full of water, noting carefully the volume of the water. Then by means of a thread lower the object into the water and read the new level of the water in the cylinder. The difference in these two readings is the volume of the object. Assuming that 1 cubic centimeter of water weighs 1 gram, we can easily get the weight of an equal volume of water.

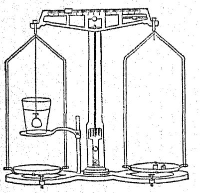


Fig. 23. Beam balance with shelf.

Another more accurate method of determining the volume of the liquid displaced is to use an aluminum cylinder or any regular solid. By means of vernier calipers (Fig. 6), one can measure the dimensions of the cylinder and compute its volume in cubic centimeters.

A more convenient and precise method of determining the weight of the solid in air and in water is to use a beam balance with an adjustable shelf, as shown in figure 23.

QUESTIONS AND PROBLEMS

1. Explain why the weight of an object in air is greater than its weight in water.

2. Why does not the overflow can always give reliable results?

3. If the volume of a rock is 1 cubic foot, how many pounds heavier will it seem to be in air than in water?

4. How does the buoyant action of water upon a block of wood vary as it is pushed into a jar of water until it touches the bottom?

5. Casks are often used to buoy up floating wharves. Would the buoyant effect of the casks be increased if the air were pumped out?

6. If you know how many pounds a solid loses in weight when submerged in water, how can you find the volume expressed in cubic feet?

EXPERIMENT 11

SPECIFIC GRAVITY OF SOLIDS

How many times heavier is a given solid than an equal volume of water?

Heavy solids (100–250 g.), such as pieces of marble, glass, metal, sulfur, etc.
Light solids, such as cork, wood, paraffin, etc.
Platform balance with set of weights and support, or spring balance (250 g.)
Lead sinker
Jar of water and thread

Introduction. The specific gravity of a substance is one of its most important characteristics. For example, the specific gravity of lead is 11.4, which means that lead is 11.4 times heavier than an equal bulk of water. The specific gravity of a substance is an abstract number and is always the same, irrespective of the unit of weight used. To determine the specific gravity of a solid, we first weigh the object, next find the weight of an equal bulk of water, and finally divide the weight of the object by the weight of an equal bulk of water. In other words,

$$\text{Specific gravity} = \frac{\text{weight of body}}{\text{weight of equal bulk of water}}.$$

In the case of a regular geometrical solid, we can measure the dimensions, calculate the volume, and from the latter get the weight of an equal bulk of water. (See Experiment 2.)

If the solid is irregular and will sink in water, we can apply the principle of Archimedes and determine its apparent loss of weight in water. This is the weight of an equal bulk of water.

If the solid is irregular and lighter than water, we can determine the weight of an equal bulk of water by means of a sinker

suspended below the object. First get the weight of the solid in air with the sinker attached and under water, as shown in figure 24 *a*. Then weigh *both* the solid and sinker submerged in water, as shown in figure 24 *b*. This weight will be less than the first, for the water buoys up the object, while in the first case it does not. The difference between the two weights is equal to the weight of the water displaced by the object.

Thus it will be seen that the various methods of finding the specific gravity of solids vary only in the manner in which the weight of an equal bulk of water is found.

Directions I. ***Solids which sink in water.*** Weigh the specimen of rock, metal, or sulfur in the usual way. Then suspend the object by a thread and weigh the solid entirely submerged in water, taking care that the specimen does not touch the sides or bottom of the jar. Air bubbles are liable to adhere to the body when submerged in water and increase the displacement; therefore it is well to remove them as far as possible by lifting the solid up out of the water for an instant.

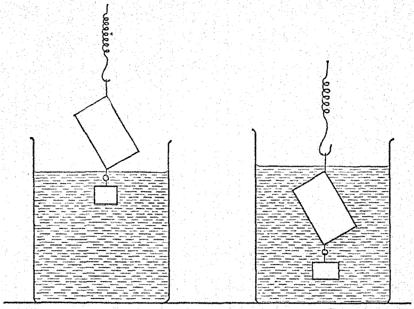
Record your observations and results in tabular form:

Substances Used	Glass	Marble	Sulfur
Weight of solid in air			
Weight of solid in water			
Loss of weight in water			
Weight of equal volume of water			
Specific gravity of solid			

Compare your values for the specific gravity of the substances tested with the table of densities given on page 10 of the revised Black and Davis' Practical Physics. *Account for the general agreement between the specific gravity as found by experiment and the densities as given in grams per cubic centimeter. Account for the differences.*

If spring balances are used in this experiment, the weights will easily be determined, but only very roughly. If platform balances are used, the scales must be supported a foot or more above the table and the object can be suspended by a thread directly under one platform. When a beam balance is used, a special device is usually provided for this experiment.

II. ***Solids lighter than water.*** First weigh the block of wood or paraffin alone in air. Then weigh the block in air with the sinker attached and in water, as shown in figure 24 *a*. (It may be more convenient to weigh the sinker under water and add this to the weight of the block in air.) Finally, weigh both block and sinker submerged in water, as shown in figure 24 *b*.



(*a*) (*b*)

Fig. 24. A light solid with sinker.

The difference between the second and the third weights is obviously due to the buoyant action of the water on the block alone, and this is equal to the weight of the water displaced by the block. From this difference and the weight of the block in air, obtain the specific gravity of the block used in this experiment.

Arrange your data and results as follows:

Weight of block of —— in air	g.
Weight of sinker in water	g.
Weight of block in air and sinker in water . . .	g.
Weight of block and sinker *both* in water . . .	g.
Lifting effect of water on block	g.
Specific gravity of block	

Since the solid is lighter than water, its specific gravity will be less than 1 and should be expressed as a decimal fraction. How many figures in your result do your data justify you in keeping?

Optional experiment. When a solid is lighter than water and regular in form, its specific gravity can often be easily determined by finding the fractional part of the whole volume that is sub-

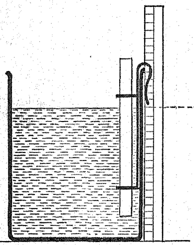


Fig. 25. A stick floating on end.

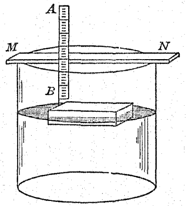


Fig. 26. How much of the block is above water?

merged. This is because the volume submerged represents the weight of the block, and the whole volume the weight of an equal volume of water.

Float a cylinder of wood endwise in water, as shown in figure 25. Measure the length under water and the whole length, and compute the specific gravity.

In case a block of wood is used, the distance which the block sinks in water can be measured by subtracting the distance which it floats above the surface of the water from the thickness of the block. This

distance which the block projects above the water may well be determined by measuring the distance of the top surface of the block below a straight edge laid across the top of the jar, as shown in figure 26, and then measuring the distance of the surface of the water below the same straight edge. The difference in these two readings gives the distance which the block projects above the water. More accurate results will be obtained if these measurements are repeated at each corner of the block. It will also assist in measuring these distances if a pin is fastened with wax to the end of the measuring stick.

QUESTIONS AND PROBLEMS

1. What practical use does a manufacturer have for a table of specific gravities?

2. Assuming that a block of wood floats in water with a centimeters of its thickness in water, and that the area of the top of the block is A square centimeters and its thickness is b centimeters, prove that the specific gravity of the block $= a/b$. (Apply Archimedes' principle.)

3. How much will a ten-pound iron ball weigh in water? Assume that the specific gravity of the iron is 7.5.

4. A cork (sp. gr. 0.25) which weighs 50 grams in air is fastened to a sinker (sp. gr. 8.5) which weighs 204 grams in air. How much will both together weigh in water?

EXPERIMENT 12

SPECIFIC GRAVITY OF A LIQUID

How many times heavier is a given liquid than water?

Jar of salt water or other liquid
Jar of water
Glass-stoppered bottle (50 $cm.^3$)
Piece of glass or porcelain
Thread
Platform balance, weights, and support, or spring balance (250 g.)
2 Hydrometers, one for heavy liquids and one for light liquids
Cloth

Introduction. Just as with solid substances, the specific gravity of a liquid is one of its most important characteristics. For example, if the specific gravity of the acid solution in a lead storage battery is 1.30, we know that the battery is fully charged; while if its specific gravity is only 1.15, we know that the battery is nearly discharged and should be recharged

immediately. Again, suppose we test the mixture of denatured alcohol and water in an automobile radiator and find its specific gravity to be 0.933. Then we can tell by tables that its freezing point is − 32° F.; while if its specific gravity is 0.975, then the freezing point is 14° F. The determination of the specific gravity of milk is one of the important tests made in its examination.

To find the specific gravity of a liquid (or solid), we divide the weight of a given specimen by the weight of an equal volume of water. One method is to use a glass-stoppered bottle to get equal volumes of the liquid to be tested and of water, and then to compare the weight of the liquid with the weight of the same volume of water. Another method is to weigh some object, like a piece of glass, in air, in the given liquid, and in water, and then to compare the loss of weight in the liquid with the loss of weight in water. The commercial method is to float a suitable hydrometer in the given liquid and to read the specific gravity directly.

Directions. I. ***Bottle method.*** First find the weight of the empty (dry) bottle and stopper; then find the weight of the bottle full of the liquid to be tested. Finally, find the weight of the same bottle full of water. It is necessary, of course, to wipe the outside of the bottle dry each time and to be sure that there are no air bubbles left in the bottle; that is, that the bottle is quite full in each case.

From these three weights we can compute the weight of a certain volume of the liquid and also of the same volume of water, and then by division we obtain the specific gravity of the liquid.

Record the weighings and computed results as follows:

Weight of empty bottle with stopper . . .	g.
Weight of bottle full of liquid	g.
Weight of bottle full of water	g.
Weight of liquid in bottle	g.
Weight of water in bottle	g.
Specific gravity of liquid	

II. ***Displacement method.*** Weigh some object, such as a piece of glass or porcelain, in air; then weigh the same object submerged in the liquid to be tested, and again weigh the object submerged in water. A platform balance when properly supported in an elevated position or a beam balance with some special device for weighing objects submerged in a liquid will give much more accurate results than the ordinary spring balance. Be sure the object when weighed in the submerged condition does not touch the bottom or sides of the jar and is fairly free from air bubbles.

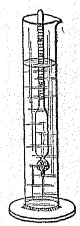


Fig. 27. Testing gasoline.

From these three weights compute the loss of weight in the liquid; that is, according to the principle of Archimedes, the weight of the liquid displaced. In the same way compute the loss of weight in water, which is the weight of an equal volume of water. Finally, by comparing these *losses in weight* in the liquid and in water, determine the specific gravity of the liquid.

Record the weighings and computed results as follows:

Weight of piece of glass in air	g.
Weight of piece of glass in liquid	g.
Weight of piece of glass in water	g.
Loss of weight in liquid	g.
Loss of weight in water	g.
Specific gravity of liquid	

III. ***Hydrometer method.*** Nearly fill a tall jar with the liquid to be tested and float the hydrometer in the liquid (Fig. 27). Read the position of the surface of the liquid on the hydrometer scale and thus get the specific gravity directly.

Optional experiment. A very rapid and precise method of comparing the density of a liquid with that of water, that is, determining the specific gravity of a liquid, is to balance a column of the liquid with a column of water, as shown in figure 28. If we suck some of the air out of the tube and then close the screw pinchcock P, it is evident that the pressure of the air on the liquids in the tumblers is

holding up the two columns. Both liquid columns exert at their bases the same pressure, which depends on the height and density of the liquid. Consequently the liquid of less density will have the greater height, and the densities of the two liquids A and B vary *inversely* as the lengths of the columns x and y. From this it follows that

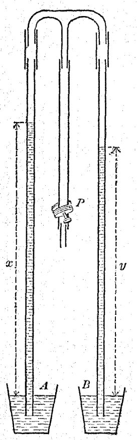


Fig. 28. Which liquid is the heavier?

$$\text{Specific gravity of liquid} = \frac{\text{Density of liquid}}{\text{Density of water}}$$

$$= \frac{\text{Length of water column}}{\text{Length of liquid column}}.$$

Set up the apparatus and make three determinations of the specific gravity of some liquid by balancing columns.

QUESTIONS AND PROBLEMS

1. Which of the methods used by you for determining the specific gravity of a liquid do you consider the most reliable? Discuss the sources of error in each.

2. In commercial laboratories the capacity of the specific-gravity bottle is usually marked on the outside and its weight is tared with a piece of brass. How can the specific gravity of a liquid be determined with such a bottle by making only one weighing?

3. What advantages has water as a standard in determining the specific gravity of other substances?

4. Compute the weight of gasoline (sp. gr. 0.75) contained in a 15-gallon automobile tank when it is full. (1 gallon = 231 cubic inches.)

5. In the South Kensington Museum, London, there is a glycerin barometer. How high would such a barometer stand when a mercury barometer reads 30 inches? (Sp. gr. of glycerin = 1.26; sp. gr. of mercury = 13.6.)

EXPERIMENT 13

WATER MOTOR

What is the horse power and what is the efficiency of a small water motor under varying loads?

Water motor to be attached to faucet	Small hard cord
Pressure gauge (0–100 lbs.) with connecting pipe	Speed counter
	Stop watch
	Gallon measure
2 Spring balances (4 lbs.) with suitable support	

Introduction. Where water is drawn from heights of a thousand feet or more, as in Norway, Switzerland, and our Sierra Nevada mountains, the Pelton or jet type of water wheel is used. The small water motors which may be operated from any faucet where the pressure is at least 30 pounds per square inch are built on the same plan. A stream of water strikes against a series of paddles or buckets fastened on the periphery of the rotating wheel.

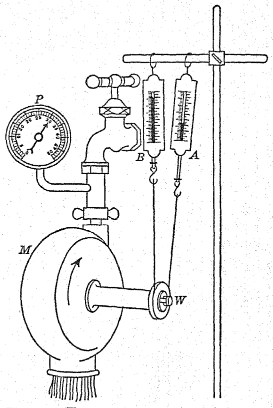


Fig. 29. How much power does the motor give?

To measure the power of the motor, that is, its rate of doing work, we may make a **brake test.** A very simple form of brake consists of a cord attached to two spring balances and passing under a pulley on the motor shaft, as shown in figure 29. If the motor rotates clockwise, as indi-

cated, it is evident that the spring balance A will have to exert more force than balance B because of the friction of the pulley on the cord. The amount of this friction is equal to the difference between the readings of A and B, and it is exerted each minute through a distance equal to the circumference of the pulley times the revolutions per minute.

Work done per minute = friction × distance per minute.

To get the **horse power**, we measure the amount of work in foot-pounds done per minute and then divide by 33,000, which is the number of foot-pounds per minute for one horse power. This gives us the mechanical **output** of the motor.

To measure the efficiency of the motor, we shall also need to determine the **input**, that is, the rate at which the water is doing work on the motor. We shall, therefore, measure, while the motor is running, the water pressure by the gauge in pounds per square inch and the volume of water (cubic inches) passing through the motor per minute. If we imagine this volume of water in a pipe 1 square inch in cross section, then its length expressed in feet will be equal to the volume in cubic inches divided by 12. Then it follows that

$$\textbf{Work done by water per min.} = \frac{\textbf{Pressure (lbs./sq. in.)} \times \textbf{Volume (cu. in.) per min.}}{12}$$

The **input**, expressed in horse power, will be equal to the work done by the water per minute divided by 33,000. The efficiency is equal to the output divided by the input.

Directions. First determine the circumference of the pulley in feet by measuring the length of fine wire required to make one turn around the pulley. Attach the motor to the faucet and turn on the water at full head. Measure the water pressure while the motor is running. With a stop watch and a gallon measure, find how many seconds are required for one gallon of water to pass through the motor. If we assume that a gallon is equal to 231 cubic inches, it will be easy to compute the

number of cubic inches of water passing through the motor in one minute.* Increase the tension on the spring balances until the motor appears to be hard at work. Determine the number of revolutions per minute of the driving pulley by means of a speed counter. For just one minute hold the speed counter firmly enough against the end of the motor-shaft to prevent slipping, but not so hard as to reduce the speed. Record the average pull on each balance.

Then repeat the experiment, putting more load on the motor by pulling more strongly on the balances. Finally, make a third trial with still more load on the motor.

It will be convenient to record the data and results in tabular form as follows:

	First Trial	Second Trial	Third Trial
Circumference of pulley (ft.) . .			
Speed in r. p. m.			
Reading of balance A (lbs.) . .			
Reading of balance B (lbs.) . .			
Friction pull ($A - B$) (lbs.) . .			
Horse-power *output*			
Gauge pressure (lbs./sq. in.) . .			
Volume of water per minute (cu. in.)			
Horse-power *input*			
Efficiency (output ÷ input) % .			

Results. From this experiment, *what is the maximum horse power obtained from the motor?*

Under what load did the motor show its highest efficiency?

What was the effect on the speed of the motor of increasing the load?

* If a water meter is available, insert it in the supply pipe and then the measuring of the water will be done by the meter.

Optional experiment. Find out the regular water rates in your locality. (If water is not sold by the meter, assume that it costs one dollar per thousand cubic feet.) Compute the cost per hour for the water consumed by the motor.

Calculate how much work in foot pounds is represented by a dollar's worth of water at the pressure of the faucet.

QUESTIONS AND PROBLEMS

1. What practical use is made of small water motors?

2. What disadvantages have small water motors as compared with electric motors?

3. What other types of water wheels, besides the Pelton, are used commercially? What advantage has each type?

4. A water wheel at Niagara is set in the bottom of a pit 136 feet deep and delivers 5000 horse power. How many cubic feet of water pass through the wheel per minute if the efficiency is 80 per cent?

5. In a certain power plant the water comes from a reservoir which is 400 feet above the water wheel. Compute the horse power of a wheel which takes 150 cubic feet of water every second and has an efficiency of 85 per cent.

EXPERIMENT 14

THE MERCURY BAROMETER

What are the principles involved in the construction and use of the mercury barometer?

Wide-mouthed bottle (8 oz.) fitted with 2-holed rubber stopper
Barometer tube, 38 inches long, open at both ends with a stopcock near one end
Mercury (2 lbs.), redistilled
Ring stand with one ring and clamp
Rubber tubing
Meter stick
Air pump, pressure, and vacuum
L-tube, 6 inches long, bent at right angles with stopcock near one end

Introduction. Probably we all know that the mercury barometer is used to predict the weather and to measure altitudes. How is it made and how does it work? We may easily answer these questions and many others about the barometer

by setting up the experimental apparatus* shown in figure 30. With this apparatus we shall be able to measure the pressure of the atmosphere and to see how atmospheric pressure varies with the weather and with the altitude.

Directions. I. Set up the apparatus as shown in figure 30. Open both stopcocks and with the pressure pump force air into the bottle until the mercury rises in the long tube just above its stopcock. Close this cock and remove the pump. Make a diagram of the apparatus.

(1) *Why does the mercury rise in the tube?*

(2) *How high (centimeters) is the mercury in the tube above that in the bottle?*

(3) *What is above the mercury in the tube?*

(4) *If the column of mercury were one square centimeter in cross section, how many grams would this column of mercury weigh?*

(5) *How much pressure must the air exert on the mercury in the bottle to hold up this column of mercury?*

II. Attach the vacuum pump to the short tube and reduce the pressure of the air on the mercury in the bottle.

(1) *Why does the mercury in the long tube go down?*

(2) *How can you measure the pressure of the air left in the bottle?*

III. Open the stopcock in the long tube and attach the vacuum pump to this tube. Exhaust the air from the tube slowly and steadily as much as the pump will permit. Close the upper stopcock.

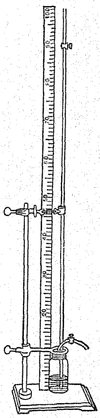


Fig. 30. Experimental barometer.

(1) *Why does the mercury rise in the long tube?*

(2) *Why does it not rise as high as in I?*

(3) *What fraction of the air has been removed from the tube by the pump?*

*This form of apparatus was designed by Mr. John C. Packard, High School, Brookline, Mass.

In answering the above questions, make complete statements and refer to the diagram of the apparatus.

Optional experiment. Repeat this experiment with a Bourdon pressure and vacuum gauge connected between the pump and the apparatus. Compare the gauge readings with the heights of the mercury in the tube.

Set up a mercury barometer essentially as in I and record its readings together with weather conditions every day for two weeks. What kind of weather usually follows or accompanies "low" barometric pressure? Learn to adjust and read a standard mercury barometer.

QUESTIONS AND PROBLEMS

1. How tall a water column would the atmosphere hold up?

2. If the mercury tube were 1 square inch in cross section and if the mercury column were 30 inches high, what would be the atmospheric pressure in pounds per square inch? Assume that 1 cubic inch of mercury weighs 0.49 pounds.

3. If the atmospheric pressure is equivalent to a mercury column 30 inches high, how many feet high would a water barometer stand?

4. Why is it essential that a mercury barometer hang vertically?

5. Compute how many tons the atmosphere is pressing upon the human body if its total area is 20 square feet. Assume that the barometer stands at 30 inches.

EXPERIMENT 15

DENSITY OF AIR

What is the weight of a liter of air under the conditions of temperature and pressure of the room?

Two-liter round-bottom flask, with 1 hole rubber stopper and connections extra strong	2 Screw pinchcocks
Air pump and mercury gauge	Y-tube
Barometer	Equal-arm balance sensitive to 0.05 g.
	Set of weights

Introduction. When riding fast we feel the air although we cannot see it. We have just learned how we may measure the

pressure of the atmosphere about us by means of a barometer. When a barometer is carried up into the air above the surface of the earth, as in an airplane, we find that the pressure decreases. All these facts indicate that we are living at the bottom of an ocean of air.

Since air is a substance which occupies space, it must have weight. Ordinarily we are not conscious of any pressure due to its weight, because it is a gas and is all around and within us. The problem of determining the weight of a definite volume of air and then computing in grams the weight of one liter of air is the same in principle as that of finding the density of any substance (See Exp. 2), but it requires more precautions. In the first place, air is so light a substance that we must use a very sensitive balance. Second, to determine the volume of the air, we use a 2-liter flask and weigh it with air and without. But we can never quite exhaust the flask and so must measure with a mercury gauge the fraction of the air removed. All in all the problem of finding the density of air will tax our patience and skill to the utmost.

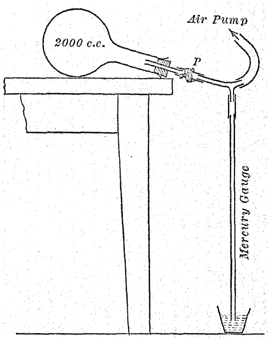


Fig. 31. **Pumping air out of the flask.**

Directions. First of all, it is assumed that the **volume of the flask** has already been determined by filling it with water and then measuring the volume of water with a graduate. When this volume has once been determined, it is marked on the flask and this part of the experiment need not be repeated; but great care should be taken to have the flask dry and clean inside and out before attempting to weigh its content of air.

Connect the flask, mercury gauge, and air pump as shown in figure 31. After pumping out some of the air, close the rubber tube connected with the pump by a pinchcock and watch the mercury gauge to see whether there is a leak in the connections. A gradual drop of the mercury would indicate such a leak, which must be stopped before proceeding. When all the connections are tight, continue pumping for at least five minutes and then *read the mercury gauge* (*i.e.*, height of mercury in tube above that in glass). Close the pinchcock P near the bottle tight.

Disconnect the flask with its tube and pinchcock, suspend it from one arm of the balance, and counterpoise its weight with great care. Without disturbing the flask or balance, open the pinchcock and let the air in. Add the necessary weights to make up for the air admitted. This added weight represents the **weight of air** admitted to the flask.

Computations. But not quite all the air was removed from the flask by the pump. In fact, only that *fraction of total volume of the flask* indicated by the height of mercury in the pressure gauge divided by the height of mercury in the barometer was removed.

Having calculated, then, the number of cubic centimeters of air admitted and its weight, we may readily compute the weight of 1000 cubic centimeters.

Since the weight of air varies greatly with the temperature and pressure, it is well to record the room temperature and barometric pressure and then check the experimental result of this rather crude method with the results given in the tables in the Appendix.

Arrange the data and calculated results in an orderly fashion and draw a labeled diagram of the apparatus.

QUESTIONS AND PROBLEMS

1. Why must the rubber tubing used in connecting up the apparatus for this experiment be extra strong?

2. Why does the mercury in the gauge rise so rapidly when the vacuum pump is first started?

3. From the results of this experiment expressed in the metric system, compute the density of air in the English system expressed as ounces per cubic foot.

4. How many pounds of air are contained in a rectangular room which is 40 × 30 × 12 feet? Assume that 1 cubic foot of air weighs 0.076 pounds.

5. How much heavier would a 100-gram brass weight be *in vacuo* than in air? Assume that a liter of air under ordinary conditions weighs about 1.2 grams.

EXPERIMENT 16

COMPRESSIBILITY OF AIR — BOYLE'S LAW

How does the volume of a given quantity of air kept at constant temperature vary with the pressure?

Boyle's Law apparatus either with a glass J-tube or with two adjustable tubes connected by rubber tubing and mounted on some convenient upright frame

Small bottle of mercury (50 $cm.^3$) if not supplied with the apparatus

Barometer

Millimeter cross-section paper

Introduction. With an ordinary compression pump we can force air into an automobile tire until the desired pressure (indicated by a gauge) is obtained. How much air at ordinary pressure has been forced into the tube to produce this pressure? If we knew this volume of air and the dimensions of the pump, then we could compute the number of strokes required. But this assumes that the pump is perfect and does not leak, and of course that is not the case with any practical pump. By comparing, however, this theoretical number of strokes with the actual number of strokes required to produce a given pressure, we can compute the efficiency of the compression pump.

But all problems which have to do with the compressibility of gases depend upon a very important principle relating to the volume and pressure of a given quantity of a gas at constant temperature. This was discovered about 1662 by Robert

Boyle. It will greatly help us to understand the meaning of this principle if we ourselves repeat his "experiments touching the spring of the air."

Directions. The simplest form of apparatus for observing the effect of varying pressures in changing the volume of a given quantity of air is doubtless the J-tube (Fig. 32), which is the form that Boyle used in his original experiments. First fasten the bent glass tube by rubber bands to the upright support. Then carefully pour mercury into the tube until the mercury covers the bend and stands a few centimeters higher in the long arm than in the short arm. Tip the tube so as to allow air to escape from the short arm until the mercury stands a trifle higher in the short arm than in the long arm. The air imprisoned in the short arm is now to be compressed gradually, and so the stand should not be tipped in any way lest some air escape. Since the short arm is assumed to be of uniform bore, the volume of the air is proportional to the length of the air column BC. By reading on the meter stick the position of the surface of the mercury B in the closed arm and the position of the top of the bore C of the tube, we can easily determine the length of the imprisoned air-column V.

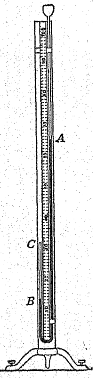


Fig. 32. Boyle's tube.

In determining the pressure we must not forget that the air is pressing on the mercury in the open arm and that this atmospheric pressure is equivalent to the pressure of the column of mercury in the barometer. If the mercury should happen to stand at the same level in both arms, then the pressure P exerted on the column of air is the atmospheric pressure and is obtained by reading the barometer expressed in centimeters. If the mercury in the open arm stands at a lower level than that in the closed tube, then the air in the tube is under less

than atmospheric pressure, and the pressure is equal to the barometric pressure *minus* the difference in levels, both expressed in centimeters. But if the level of the mercury in the open arm is higher than it is in the closed arm, then the air is under more than atmospheric pressure, and the pressure is equal to the barometric pressure *plus* the difference in levels.

By pouring in more mercury, it is possible to increase the pressure P on the inclosed air from less than one atmosphere to two atmospheres and to observe the resulting changes in the volume V of the air in the tube. Since the volume of a gas is very sensitive to changes in temperature, it is well not to handle the air column with the warm hands. In reading the position of the mercury on the meter stick, be sure that your eye is on a level with the mercury and that you read the top of the mercury surface each time.

Record the reading of the barometer at the time of the experiment. Record also the positions of the mercury-surface in the closed arm B and in the open arm A. Pour in mercury so as to make the level in the open arm about 20 centimeters above that in the closed arm and record the mercury levels in each arm. Continue this process of adding mercury (about 20 cm. each time) and reading the levels until the volume of the air is compressed to about one half of its original volume.

Record your readings and computed results in tabular form as follows, keeping only significant figures in the last column:

Position of upper end of air column C . . . cm.
Atmospheric pressure (barometer) . . . . . cm.

Position of Mercury in Open Tube (A)	Position of Mercury in Closed Tube (B)	Difference in Mercury Levels	Total Pressure P	Volume of Air V	Pressure Times Volume $P \times V$
cm.	cm.	cm.	cm.		

Results. By comparing the values obtained in this experiment for the total pressure P and for the volume of the air V, it will be evident that when the *pressure increases* the *volume decreases*. But this relation may be expressed more precisely. If we multiply in each trial the total pressure by the corresponding volume, we find that the resulting products, PV, are nearly **constant**. In other words,

$$P_1 \times V_1 = P_2 \times V_2 = P_3 \times V_3, \text{ or } \frac{V_1}{V_2} = \frac{P_2}{P_1} \text{ and } \frac{V_2}{V_3} = \frac{P_3}{P_2}.$$

In general, then, we find that the volume of the air in the tube varies *inversely* as the pressure. This means that when the pressure is doubled the volume is halved.

Graphical representations of results. If we compute the average value of PV, we can, by using this constant, find the pressures which would correspond to two, three, and four times the greatest observed volume. In the same way we can find the volumes which would correspond to two, three, and four times the greatest measured pressure.

Plot these six pressures with their corresponding volumes and also the observed pressures and volumes. Represent the pressures as vertical distances and the volumes as horizontal distances. Draw a smooth curve through these points, using a solid line through the observed points and a dashed line through the six computed points.* Note that this curve, if continued, would come very close to, but never quite touch, the axes. Such a curve is called a **hyperbola.**

Other forms of apparatus. Since it is difficult to pour mercury without spilling it and since this experiment is of fundamental importance, many other forms of apparatus have been devised.

In one form (Fig. 33) we have two glass tubes of which one is closed with a stopcock and is graduated into cubic centimeters and the other is a plain glass tube. These are connected by a

* For further suggestions about plotting curves, see Appendix.

flexible rubber tube. The tubes are supported by clamps which may be moved along a vertical scale. Mercury is poured into the open tube so as to imprison some air in the closed tube. The various pressures are obtained not by pouring in more mercury but by raising or lowering the tubes. Thus we obtain the volume directly and compute the pressure from the barometer and difference in levels of the mercury, just as previously described.

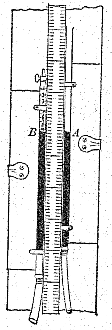


Fig. 33. Apparatus with sliding tubes.

In another form we have two tubes, one short closed tube and another, a longer tube, which is open, but both dipping into a bottle of mercury. A small bicycle pump is used to make the mercury rise in the two tubes. The volume of the imprisoned air and the pressure exerted upon it are computed as with the J-form of apparatus.

There is another form of apparatus which consists of a straight glass tube about 110 centimeters long with a bore from 1 to 1.5 millimeters in diameter. This tube should be prepared with great care so as to contain a column of mercury about 30 centimeters long and about 25 centimeters of inclosed air. The tube is mounted so that it may be turned into various

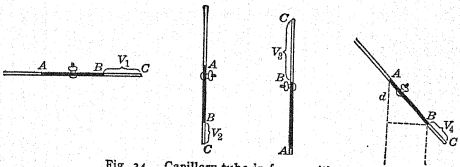


Fig. 34. Capillary tube in four positions.

positions (Fig. 34). When it is held horizontally, the air is under atmospheric pressure; when it is held with the open end up, the pressure is atmospheric plus the pressure of the

mercury column; when it is held with the open end down, the pressure is atmospheric minus the pressure of the mercury column. When the tube is in some oblique position, the pressure is computed by taking not the length of the mercury column but the *vertical* height of the column. This apparatus is easy to manipulate but difficult to ship.

QUESTIONS AND PROBLEMS

1. In the J-form of Boyle's apparatus is it necessary to have the bore of the open arm uniform in cross section?

2. In the form of apparatus in which the open and closed tubes are connected with a rubber tube, does the length of the rubber tubing have to be considered? Explain.

3. In the apparatus which consists of a long capillary tube with a mercury column in the middle, what would be the effect of an air bubble in the mercury column?

4. From your study of the compressibility of air, how would you expect the volume V of air to vary with the reciprocal of the pressure $1/P$? Try for several cases.

5. An automobile tire contains an inner tube about 2.25 inches in diameter and 84 inches long. If atmospheric pressure is 15 pounds per square inch, how many cubic inches of air must be forced into the tire to give a pressure of 60 pounds per square inch? Assume that the tube is flat to start with.

6. If the inside diameter of the pump cylinder is 1.5 inches and the length of stroke is 15 inches, how many strokes, assuming no leakage, will be required in the preceding problem?

EXPERIMENT 17

MEASUREMENT OF GAS PRESSURE

I. *At what pressure is the illuminating gas supplied to your laboratory?*

II. *How much lung-pressure can you exert?*

U-tube (about 20 cm.)	Open-tube mercury manometer with arms 25 and 50 cm. long
Stand for supporting U-tube	Glass mouthpiece
Metric scale	Barometer
Rubber tubing (about 60 cm.)	

Introduction. When the gas cock is open, the illuminating gas flows out because the pressure in the gas mains is greater than that of the atmosphere. The failure of gas heating apparatus to operate satisfactorily is often due to inadequate pressure in the mains. With a water manometer it is a very simple matter to determine this pressure by measuring the difference in water levels in the two arms of the U-tube.

When larger pressures are to be measured, as for example lung-pressure, mercury is substituted for the water in the U-tube, since mercury is 13.6 times heavier than water. When still greater pressures, such as those carried in automobile tires, in the air-brake system on trains, or in steam boilers, are to be measured, a closed-arm mercury manometer is used or, in commercial work, the Bourdon gauge. The closed-arm manometer operates according to Boyle's Law. Since Bourdon gauges are often calibrated by manometers, it will be worth while to study the construction and use of the latter with some care.

Directions. I. ***Gas pressure.*** Add enough water to the U-tube to fill it about halfway up. The water levels in the two arms will be at the same height because the air is pressing down equally on both water surfaces. Connect the arm having the elbow by rubber tubing with the gas cock (Fig. 35),

and turn on the gas slowly. Read and record the position of the water surfaces in each arm. Compute the difference in water levels in the two arms. Turn off the gas and repeat this operation three times. Compute the mean, or average, value for the difference in water levels.

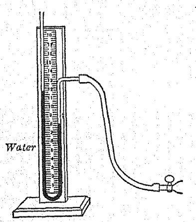


Fig. 35. Testing gas pressure.

Read and record the atmospheric pressure (barometer).

Computations. This difference in water levels is due to the increased pressure caused by the illuminating gas. It is quite independent of the cross section of the U-tube. We may therefore consider that this cross section is 1 square centimeter, and calculate the pressure in grams per square centimeter of a column of water equal in height to the difference of levels. This may be called the **effective pressure** of the gas.

To get the total, or **absolute, pressure** of the gas, we have to add the effective pressure to the atmospheric pressure. We reduce the barometric reading to grams per square centimeter and add this to the effective pressure expressed in the same unit.

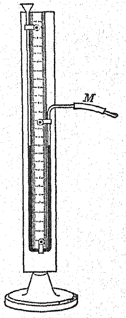


Fig. 36. Manometer for lung pressure.

Commercially gas pressure in this country is expressed in inches of water. Express the effective pressure of the gas tested in inches of water. (1 inch = 2.54 cm.)

Calculate also the total pressure in pounds per square inch, remembering that a pressure of 14.7 pounds per square inch is equivalent to the pressure of a column of mercury 30 inches, or 76 centimeters, in length.

Show clearly each step in your computations.

II. ***Lung-pressure.*** Set up the mercury manometer as shown in figure 36. Record the level of the mercury in the long arm. Then blow *steadily* * for two or three seconds into the mouthpiece, which is connected by rubber tubing with the short arm. While still blowing, pinch the rubber tube hard and then read and record the level of the mercury in the long arm. Each time read the top of the curved mercury-surface.

Of course the mercury went down in the short arm as far as it went up in the long arm of the U-tube, and so the difference in mercury levels is *twice* the difference between the two observed readings. Repeat this experiment two or three times and record each trial and the average value of your effective lung-pressure in centimeters of mercury.

Calculations. Express this effective lung-pressure as grams per square centimeter, also as pounds per square inch, and in atmospheres.

Optional experiments. Test the accuracy of a Bourdon vacuum gauge by connecting it in series with a tall (about 100 cm.) U-tube manometer partly filled with mercury. By means of a vacuum pump exhaust the air slowly, and at various stages in the process read the gauge and the difference in mercury levels in the two arms. Compute the error, if any, in each gauge reading.

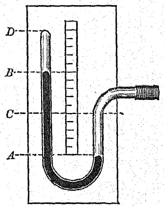


Fig. 37. Closed-tube manometer.

In the same way test the accuracy of a Bourdon pressure gauge. For pressures above 15 pounds per square inch, it will be more convenient to use a closed-arm manometer such as that shown in figure 37 and apply Boyle's Law.

If a small steel tank is available, it will be easy to arrange apparatus so as to test the accuracy of the automobile-tire gauge which is in ordinary use.

* If you give a quick hard blow into the mouthpiece of the mercury manometer, you will get a higher reading of the mercury than your true lung-pressure. *Why?*

QUESTIONS AND PROBLEMS

1. Would it have been more accurate to use gasoline in the U-tube instead of water to measure the gas pressure?

2. Why is the gas pressure at any particular stopcock not always the same?

3. Why was it not necessary to remove the air in the arm of the U-tube connected to the gas pipe?

4. Why is it advisable to use a glass mouthpiece in the lung-pressure experiment?

5. Compute the average lung-pressure of the class.

6. Compute what per cent your own lung-pressure is of the class average.

7. Suppose that a glass U-tube was not at hand and that a straight glass tube was placed in a jar of water and connected to the gas supply. Explain how this simple apparatus could be used to measure the gas pressure.

EXPERIMENT 18

CONCURRENT FORCES — PARALLELOGRAM LAW

When three non-parallel forces are acting on a body, what must be their relative directions and magnitudes in order to produce equilibrium?

Three spring balances (2000 g.)	Fishline
Three table clamps	Block of wood
30-cm. ruler	Pencil compass

Introduction. Thus far we have been studying machines in which the forces are parallel. In many practical structures, however, such as roofs and bridges, and in many machines, such as sailboats and airplanes, we have forces which are applied at the same point or, if extended, pass through the same point. Such forces are called **concurrent forces.** In this experiment we shall study the conditions under which concurrent forces are in equilibrium, that is, balance each other so that no motion is produced. Take, for example, the

case of a rope fastened horizontally to two supports and a weight, such as a street-lamp, hung on the rope (Fig. 38). Suppose we know the weight of the lamp and the angle of sag and wish to find the tension in the ropes. Evidently here we have three concurrent forces in equilibrium.

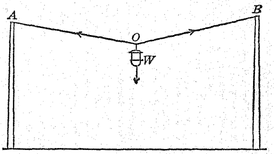


Fig. 38. Lamp supported by rope.

It will greatly simplify the solution of such problems if we represent each force by an arrow drawn to scale. The length of the arrow will show the magnitude of the force, its tip will show the direction of the force, and the tail of the arrow will show the point of application of the force.

Directions. To the middle of a piece of fishline about 40 cm. long tie a second piece about half as long. At each of the free ends make a loop and attach the hook of a spring balance. To the ring of each balance attach a strong string, and then arrange on the table the clamps, balances, and strings as shown in figure 39.*

Pull each balance until its index is about in the middle of the scale, where it is most reliable, and then slip a right-hand page of the notebook under the cord connecting the balances so that the knot comes about in the middle of the page.

In order to show the direction of each cord on the paper, place a rectangular block alongside and draw a line directly under each cord. Record beside each line the force indicated by the balance, and then relieve the tension on the spring balances. Observe the zero reading of each balance in a horizontal position and apply the proper correction to the reading

* In some laboratories it may be more convenient to arrange the apparatus in a vertical plane, using a weight and two spring balances, or three weights and two fixed pulleys. To prevent slipping of the cords at the knot, a small ring (about 1 cm. in diameter) is sometimes used.

just recorded. If the zero reading is less than zero, add the correction to the balance reading recorded on the paper; if it is more than zero, subtract the proper amount.

Graphical construction. If the experiment has been carefully done, the three lines representing the three forces will, when prolonged, intersect at a common point. Measure off on each line a distance corresponding to the force, according to any convenient scale, such as 200 grams to 1 centimeter. Make

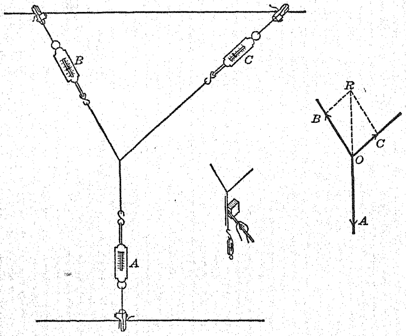


Fig. 39. Three concurrent forces.

an arrowhead at the end of each measured line and erase that part of each line which lies beyond the arrowhead.

On any two of these lines construct a parallelogram, using a ruler and pencil compass to get the lines exactly parallel. Draw the three original force lines (*OA*, *OB*, and *OC*) as solid lines, the lines needed to complete the parallelogram (*BR* and *CR*) as dotted lines, and the diagonal (*OR*) as a broken line. Draw the diagonal of this parallelogram from the central point, measure its length, and compute the magnitude of the force which

it represents. For example, a line 15.6 centimeters long represents a force of 3120 grams when the scale is 200 grams to 1 centimeter. This diagonal line represents the **resultant** of the two forces which form the sides of the parallelogram.

The third force OA, which balances these two forces OB and OC, is called their **equilibrant.**

How does the resultant of two forces compare with their equilibrant (a) in magnitude and (b) in direction?

In a similar way determine the resultant of each of the other pairs of forces, regarding the third force in each case as the equilibrant.

Make a second trial using different angles and forces, and repeat the constructions on another page.

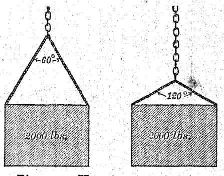


Fig. 40. How to rope a crate.

State in your notebook what you have proved to be true regarding both the magnitude and the direction of the resultant of two concurrent forces.

Optional experiment. Arrange your apparatus so that you will have **four concurrent forces.** Represent them graphically as just described and find the resultant of any pair of the forces. Then find the resultant of this resultant and a third force and compare this resultant of three forces with the fourth force considered as an equilibrant.

State the general condition of equilibrium for concurrent forces.

QUESTIONS AND PROBLEMS

1. Why will the results in this experiment be more accurate if a large parallelogram is drawn?

2. Suppose a motor boat has a speed of 12 miles an hour north, but the wind drives it eastward at the rate of 5 miles an hour. Find the direction in which the boat goes and the actual distance covered in one hour.

3. A crate containing a piece of machinery weighs one ton and is to be lifted by a crane as shown in figure 40. What is the force exerted by the chain?

4. If the rope around the crate (problem 3) makes an angle of 60 degrees at the crane hook, what is the tension in the rope?

5. If the rope around the crate (problem 3) makes an angle of 120 degrees at the crane hook, what is the tension in the rope?

6. From these problems what do you learn about the proper way of attaching a rope to a heavy weight for hoisting?

EXPERIMENT 19

A SIMPLE CRANE

How great is the thrust exerted by a boom and how great is the pull exerted by a tie rope when used to support a weight?

Simple truss with a light stick and a foot support (Pratt Institute model)	Two spring balances (20 lbs.) Weights and hanger Large protractor

Introduction. One of the simplest practical applications of the parallelogram law for concurrent forces is found in a crane or derrick. The same law applies to the case of a street lamp or any other weight hung out on a bracket from a pole (Fig. 41). In all such cases we have a downward force caused by the load W, an outward thrust or push P exerted by the boom or stick, and an oblique pull T exerted by the tie rod. These three concurrent forces are in equilibrium. Our problem in this experiment is to find how much the thrust exerted by the boom is and how much the pull exerted by the tie rod is when we know the load and the direction of the other two forces. Then we shall be able to check the accuracy of our computed values for these forces by actually measuring the forces with spring balances. From our experience in the solution of such problems, we may develop a certain amount of common sense,

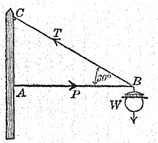


Fig. 41. How much push P and how much pull T?

which will greatly help us to solve approximately such problems, even without experimenting.

Directions. I. ***Boom horizontal.*** Figure 42 shows a laboratory model of a simple crane, or truss, in which the weight of the stick BC may be neglected because it is so small in comparison with the other forces. Set up the apparatus so that the stick is horizontal. Add enough weights at W to stretch the balance F nearly to its full scale reading.

Measure with a large protractor the angles ACB and BCW and record the load W and the pull exerted by the tie rope as indicated by the balance F. To measure the thrust exerted

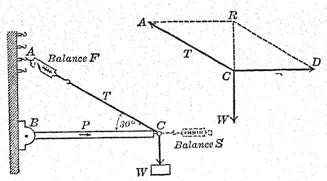


Fig. 42. What are the forces P and T?

by the stick, attach a second balance S at the outer end of the stick and pull out in line with the stick until the end of the stick at B just leaves the support.

To compute the force exerted by the tie rope, we have merely to draw a careful diagram of the three forces acting at the point C. Use a full page for this diagram and make the scale as large as the space will permit. First lay off to scale the vertical line CW to represent the weight, then draw the force lines to show the direction of the thrust and of the pull. Extend upward the weight line CW as a dashed line its own length CR, and from R construct parallel dotted lines RA and RD. Where these lines cut the force lines, place arrowheads. Measure these forces CA and CD as thus constructed and compute the value of the forces. Compare these calculated

values with the observed values as measured on the spring balances.

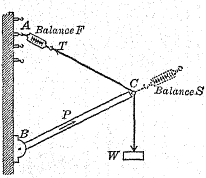


Fig. 43. Effect of raising the boom.

II. ***Boom not horizontal.*** Change the angle of the stick to the wall as shown in figure 43 and repeat the experiment, making the force diagram and taking the check readings as before.

If time permits, set the boom at some other angle and get a third set of readings.

Tabulate your readings and results as follows:

TRIAL	LOAD W	$\angle ACB$	$\angle BCW$	PULL F		THRUST S	
				Computed	Measured	Computed	Measured
I							
II							

Optional experiment. Set up a laboratory model of a simple roof truss as shown in figure 44. Compute and measure the upward thrust at A and the horizontal pull exerted by the tie rod. In this case the weight of the members AB and BC must be determined and considered as well as the load W. Construct a diagram of the three forces exerted on the pin at B and at A. Half the weight of the member AB may be considered to be acting downward at A and half at B.

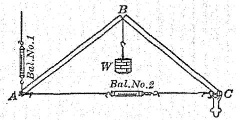


Fig. 44. Forces acting on a roof truss.

QUESTIONS AND PROBLEMS

1. How do you account for the differences between your computed and measured values of the pulls and pushes in this experiment?

2. How would you proceed to compute these forces in a case where the boom is horizontal and the load is suspended from the *mid-point* of the boom?

3. In a certain experiment like case I, the load is 12 pounds and the angle ACB is 30°. Compute the tension in the tie rod and the compression in the stick.

4. If the stick is 10 feet long and placed at an angle of 45° to the wall, what is the tension in the tie rod which is horizontal when the load is 1 ton? What is the compression in the stick?

5. If the stick in problem 4 remains in the same position but the tie rod is attached to the wall at a point higher up so as to make an angle of 45° to the wall, what is the tension in the tie rod? What is the compression in the stick?

EXPERIMENT 20

THE BRIDGE TRUSS

I. *Which members of the bridge truss are in tension? which in compression?*

II. *How much is the force in each member as measured and as calculated?*

Experimental Bridge Truss (Davis model shown in figure 45 *)
Test member
Spring balances
Heavy weights and hanger

Introduction. A modern bridge truss is made up of a series of triangles, and each side of the triangle, called a **member**, has to push or pull on the pins at the corners to keep the truss in position. A member which has to pull at each end is said to be "*in tension*"; and one that has to push at each end is said to be "*in compression.*" It will greatly help one to decide whether a member, in a given instance, is in tension or compression, to imagine what would happen if the given member were cut. Remember that the tension members *pull* and the compression members *push outward.* What difference in construction do you find in real bridges between the tension and compression members?

* This model was designed by Professor H. N. Davis of the Harvard Engineering School, and is manufactured by the L. E. Knott Apparatus Co., Boston. A special descriptive circular is furnished with each model.

The loads which a bridge truss must carry include the weight of the bridge itself and also the weight of the trains, cars, trucks, and people on the bridge. We shall study the effect of a single concentrated load, such as a steam roller. At first we shall neglect the weight of the bridge itself and confine our attention to the effect on each pin of a single weight.

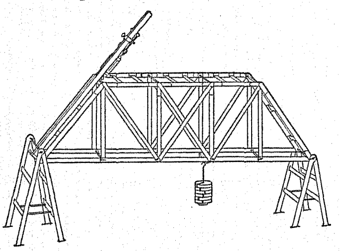


Fig. 45. Experimental model of a bridge truss.

In this way we shall be able to determine the nature and amount of the stress in any member of the truss by applying the parallelogram law for the concurrent forces acting on each pin in succession.

Directions. Set up a "four-panel Pratt truss" as indicated in figure 46 and put a load of from 40 to 60 pounds on pin E. Draw a careful diagram of the bridge truss in your notebook, indicating the compression members by heavy lines and the tension members by light lines. To find out what is the function of any given member in the model bridge, try pulling together the two end-pins with your two hands. If

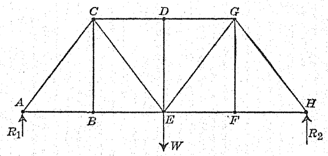


Fig. 46. A four-panel truss.

the member is in tension, you will hear a little metallic click on account of the free play at the joint. If the member is in compression, you will have to push the pins apart to produce the click.

The stresses produced in each member of the bridge may be measured by means of the *special test member*. This is attached in such a way that the stress is measured by two spring balances and will just overcome the tension or compression in the bridge member and leave the latter slack. The force in the test member can be adjusted by means of turnbuckles and, by reversing one end, can be made to measure either tension or compression.

Set up the test member to measure the tension between the pins B and E and tighten the turnbuckle until the truss members on each side are just beginning to be loose. Then read the balances and add their readings. This gives the observed tension in the member BE. Since some of it is due to the weight W and some to the weight of the truss itself, repeat the test with the weight W removed. This result is the stress due to the weight of the truss alone. Subtract it from the first result to get the part due to the weight W by itself.

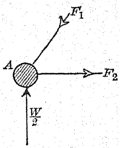


Fig. 47. Forces on A.

Next, set up the test member to measure the compression between the pins A and C and test with and without the load W on E.

Repeat the test on the member CD and also, if time permits, on BC and CE.

Computations. To compute the tension in the member BE, we shall need to consider the three forces acting on pin A at the left end of the bridge, as indicated in the **isolation sketch** shown in figure 47. We know that the upward thrust must be half the load $(\frac{W}{2})$, neglecting for the present the weight of the truss, and we know the direction of the pull AB and the push AC. We can solve for these stresses by the law of parallelogram of forces, in which we shall find that the parallelogram is made of two triangles which are similar to the bridge triangle ABC. Since the sides of this triangle are 1.5 feet, 2 feet, and 2.5 feet, we can prove that the compression stress AC is $\frac{5}{8}$ W and the tension stress in AB is $\frac{3}{8}$ W.

If we now consider the forces acting on pin B, we see that the tension in AB must be equal to the tension in BE. Also the stress in BC must be zero. *Why?*

Next let us make an isolation sketch of the forces acting on pin C. Here it would seem that we had four forces; but the stress in BC is zero. We know that the push in AC is $\frac{5}{8}W$, and we wish to find the pull in CE and the push in CD. Applying the parallelogram law, we shall have two triangles, each of which is similar to ACE. And so we can prove that the compression stress in CD is $\frac{5}{8}W$ and the tension stress in CE is $\frac{3}{4}W$.

Record your observations and computed results in tabular form:

Members	BE	AC	CD	BC	CE
With load					
Without load . . .					
Net stress					
Computed stress . .					
Error					

Optional experiment. Set up the model bridge as a "five-panel Pratt truss." Show by the method just outlined why the middle section has *crossed diagonals*, which are called "*counters*"; and also show that *at any one time only one of the counters is working.*

QUESTIONS AND PROBLEMS

1. Suppose a roof truss is made up of but two panels, similar to the end panels used in the model bridge truss. Draw a careful diagram showing the compression and tension members, and compute the amount of the stresses, assuming the load W is applied to the ridgepole. This is called the "*King Post Truss.*"

2. In this type of truss what is the function of the vertical member?

3. If the above truss is inverted, it becomes the "*under-slung King Post Truss.*" Draw a complete diagram of this type of truss and compute the stresses in each member when the load W is placed in the middle of the top of the truss.

4. What difference would it make if the load were concentrated at the lowest point of the under-slung King Post Truss?

EXPERIMENT 21

BREAKING STRENGTH OF WIRE

I. *How much force is needed to break wires of various materials?*
II. *What is the tensile strength (pounds per square inch) for each material?*

Wire-breaking apparatus	Spools of steel piano wire, brass wire,
Spring balance (10 kg.)	and copper wire, both soft and hard
Micrometer caliper	drawn (about No. 28 A. W. G.)

Introduction. When a rope is used to tow an automobile or a boat, the rope is said to be in a state of **tension.** If the tensile strength is not enough for the purpose, the rope breaks. Thus it will be readily seen that one of the most important physical properties of materials is their tensile strength. It may be

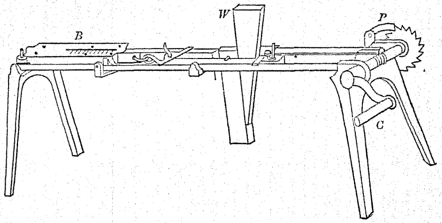


Fig. 48. Testing the strength of wire.

expressed in pounds per square inch or as kilograms per square centimeter. In our experiment we shall find the breaking strength of wires of various materials and then compute the strength in pounds per square inch on the assumption that the tensile strength varies directly as the area of cross section.

Directions. The apparatus shown in figure 48 is so designed that the tension on the wire at the instant it breaks is recorded

on a spring balance (B). The tension is applied by means of a crank (C) which turns an axle on which the wire is wound. The other end of the wire is attached to the spring balance by means of a frame. As this frame is pulled, a wedge (W) drops down which holds the index of the balance just where it was at the instant of breaking.*

First slip one end of the wire through the hole in the crank shaft and bend the end over sharply so that it extends along the shaft. In this way one or two turns of the handle will cause the wire to wind over the end and so fasten it securely.

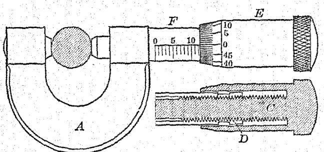


Fig. 49. Micrometer caliper showing the screw.

Pass the other end of the wire a couple of times around the wooden post on the sliding frame and clamp the end under the binding post. There must be no kinks or short bends in the wire. Let the wedge rest lightly in the slot of the sliding frame. Set the pawl (P) so that it will rest on the toothed wheel attached to the shaft and prevent the shaft from turning backward.

Now turn the crank slowly and cause a slight tension in the wire. Measure with a micrometer caliper † the diameter of the

* If this testing machine is not available, the wire can be fastened at one end to some firm support, such as a gas pipe, and at the other end to the hook of a spring balance. The stress is furnished by pulling with the hands on the spring balance. Another method is to suspend a pail by the wire to be tested. One end of the wire is attached to some stout iron rod clamped so as to project over the edge of the table. Now gradually add weights until the wire breaks. Then weigh the pail and contents with a spring balance.

† **Micrometer caliper.** This instrument (Fig. 49) is used to measure the diameter of wires, rods, and spheres, and the thickness of sheet metal. It consists of a screw moving in a nut toward or away from a fixed stop. The

wire to one thousandth of an inch, and increase the tension on the wire by turning the crank and keeping the wedge down in the slot until the wire breaks. As the wedge fills the slot, it holds the spring balance at just the position it was in when the wire broke. Record this force in pounds.

Repeat the experiment several times, using each time a new piece of wire, and find the average of these readings for the breaking strength of the given specimen of spring brass wire. Reject any trials in which the wire breaks at either fastening. If time permits, test also steel wire and copper wire.

Computations. Compute the cross-sectional area of each kind of wire, using the mean value of the diameters as measured. Then calculate the tensile strength (pounds per square inch)

distance between the threads of the screw (if metric) is usually 0.5 of a millimeter. Therefore one complete revolution of the milled head changes the distance between the jaws by exactly 0.5 of a millimeter — a fraction of a turn by a proportional amount. The head of the screw (which is inside the sleeve) is divided into 50 divisions. Therefore when the head is turned through one of these small divisions, the distance between the jaws is changed $\frac{1}{50}$ of 0.5, or 0.01, of a millimeter.

The object to be measured is placed between the stop and the end of the screw, and the latter is turned down upon it. *Avoid undue force as the instrument is easily injured. Stop turning the screw just as soon as you feel that contact has been made.* Count the number of millimeters and half millimeters on the linear scale exposed to view and add to this result the fraction of the last division obtained by reading the circular scale. The zero error should be determined before and after measuring by taking readings with the jaws closed. Apply this correction to all readings. With the micrometer caliper just described it is possible to measure with absolute certainty to 0.001 of a centimeter and to estimate to 0.0001 of a centimeter.

When the micrometer screw is graduated in the English system, the pitch of the screw is generally $\frac{1}{40}$, or 0.025, of an inch. The linear scale is divided into tenths of an inch and each tenth into four equal parts, or fortieths (0.025) of an inch. The head of the screw is divided into twenty-five equal parts. Therefore when the screw is turned through one division on the circular scale, the screw moves lengthwise $\frac{1}{25}$ of 0.025, or 0.001, of an inch.

of each material from the fact that the breaking strength varies directly as the area of cross section. That is,

$$\textbf{Tensile strength (lbs./sq. in.)} = \frac{\text{breaking force (lbs.)}}{\text{cross section (sq. in.)}}$$

The data and results may well be recorded in tabular form as follows:

KIND OF WIRE	DIAMETERS	CROSS SECTION	BREAKING FORCE	TENSILE STRENGTH
Spring brass	— in. — —		— lbs. — —	
Mean	—	—	—	lbs./sq. in.

Optional experiment. Determine whether annealing a spring brass wire increases or decreases its tensile strength. Heat about an inch of the specimen to be tested in the middle. Find the breaking strength of the wire. Did the wire break where it was heated? Compare the diameter of the wire at the break with the diameter at some other point. Repeat the above experiments in order to confirm your observations.

QUESTIONS AND PROBLEMS

1. Compute the tensile strength (lbs./sq. in.) for hard-drawn copper wire if a specimen 0.040 inches in diameter breaks under a load of 84 pounds.

2. Compute the tensile strength (lbs./sq. in.) of hard-drawn copper wire if a specimen 0.46 inches in diameter breaks under a load of 8100 pounds.

3. How do you account for the difference in tensile strength as found in problems 1 and 2?

4. What is the influence of chemical composition on the tensile strength of steel? Consult some Mechanical Engineers' Handbook such as Marks.

5. An iron bar is to be subjected to a force of 50,000 pounds and is to be designed so that the pull shall not exceed 2500 pounds per square inch. What should be the area of its cross section, and if round, what should be its diameter?

EXPERIMENT 22

ELASTICITY OF SPIRAL SPRINGS — HOOKE'S LAW

How does the stretching of a spring vary with the force applied, provided the elastic limit is not exceeded?

Spiral spring	Mirror scale and support
Set of weights	Marker

Hanger or pan for weights

Introduction. We have already seen in Experiment 21 that when a force which is more than the tensile strength of a wire is applied to it, the wire snaps or breaks. But if we apply the load gradually, each time removing the load, we shall find that the wire stretches and, up to a certain load (called the **elastic limit**), recovers its initial length again. This property of a material is called its **elasticity.**

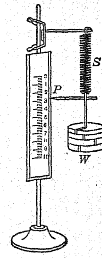


Fig. 50. How much did it stretch?

We make use of this property of spiral springs in spring balances, in door-closing devices, and the shock absorbers used on automobiles. In this experiment we shall determine how the stretching or elongation of a spiral spring varies with the force applied. This relation is known as Hooke's Law because it was first stated about 1678 by an Englishman named Hooke.

Directions. Suspend the spring from some convenient support and attach at the lower end a hanger or pan for the weights. Fasten the marker also to the lower end of the spring. Set up the mirror scale vertically very near the marker but not quite touching it (Fig. 50). Note the position of the marker on the scale,* reading to tenths of millimeters, and record this as the zero reading.

*Avoid the error called *parallax* by keeping the eye in such a position that the marker hides its reflected image.

Place a 100-gram weight on the hanger or pan; note the position of the marker and record as before.

Remove the load and record the no-load reading. Now place a 200-gram weight on the hanger, read, and record as before.

In this way gradually increase the load up to 500 grams and after each loading remove the weights and record the zero reading. Each time the marker should very nearly, if not quite, return to its initial reading. If it does not so return approximately, the spring has stretched beyond its elastic limit.

Tabulate the data and results as follows:

Load	Zero Reading of Marker	Reading of Marker with Load	Stretch of Spring
100 g.			
200 g.			
300 g.			
400 g.			
500 g.			

Results. *State the numerical relation which you have found to exist* (except for small experimental errors) *between the stretching of the spiral spring and the corresponding forces applied to it.*

Plot a curve on cross-section paper to show graphically the relation between the stretch of the spring and the force applied. Let the distances along the X-axis (horizontally) represent the forces and the distances along the Y-axis (vertically) represent the stretches. Choose a scale for plotting the quantities so that the graph will occupy nearly a full page of coördinate paper.

Optional experiment. Calibrate a spring balance by hanging various known weights from the hook and reading the position of the index on the scale. If the scale reading is greater than the weight that produced it by a certain amount, it is said to have a positive (+) error of that amount; and if any reading is less than the weight producing it, then the error is negative (−). Plot a curve showing

the errors along the scale, placing the positive errors above the horizontal axis and the negative errors below.

QUESTIONS

1. What kind of curve represents graphically Hooke's Law? State this law as an equation.

2. Will all springs stretch the same per 100 grams? Upon what factors does the stretch per 100 grams depend?

3. Would you expect a very sensitive spring balance which was calibrated at sea level to give correct readings on top of a high mountain? Explain.

4. Would you expect the readings of such a spring balance to be affected if taken from the equator to the north pole? Explain.

EXPERIMENT 23

BENDING OF RODS

How does the bending of a rod vary under different loads?

Rods of wood, steel, or brass (110 cm. × 1 cm. × 1 cm.)
△ Supports
Board to support apparatus
Meter stick
Indicator lever or micrometer screw with cell and telephone receiver
Vertical scale
Set of weights
Hanger or pan for weights

Introduction. If you walk along a plank which is supported at each end, the plank bends down more or less according to your weight, your position on the plank, and the dimensions and material of the plank. Even steel girders used in buildings and bridges are bent a little under the loads they carry. In construction work care must be taken that no part will ever be subjected to a stress greater than its **elastic limit**; for if this were to happen, the part would be permanently deformed, or at least thrown out of alignment. An engineer in designing a building plans to make each part big enough to carry several times (**factor of safety**) as much load as will probably ever be

imposed on it. This is to provide for unexpected overloading and defects in materials, and also to prevent deflections in the walls and ceilings great enough to crack the plaster.

From the study of the behavior of small test pieces, engineers have been able to predict how a full-sized member will act. In our experiment we shall be able to show how rods or beams supported at each end bend under varying loads placed in the middle, provided we do not exceed the elastic limit.

Directions. Place the board across the gap between two laboratory tables and set up the apparatus as shown in figure 51.

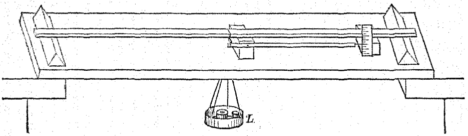


Fig. 51. Magnifying the bending of a rod with a lever.

Of course we should expect a rod to bend more with a heavy load than under a light one, and so in this experiment we shall try to show just how this bending varies with different loads (L). Since the rod gets a permanent "set," or bend, when loaded beyond a certain point, called the "elastic limit," we must each time remove the load and read the zero point. The amount of bending which a rod will stand and from which it will still recover is very small, and so some special method has to be adopted to measure this deflection, such as the magnifying lever shown in figure 51 or the micrometer screw shown in figure 52.

If the short arm of the lever is made one fifth as long as the long arm, then it will magnify the deflection 5 times. It will be necessary to read the pointer on the scale with great care (to 0.01 cm.) and to avoid the error of parallax by keeping the eye on a level with the pointer. If possible use a mirror scale here. In case the micrometer screw is used, it is necessary to

place a contact clamp on the center of the rod and then set the micrometer screw on the table so that the tip of the screw will hit the clamp. Connect a telephone receiver and one dry cell in series with the screw and the clamp, so that when the screw is turned down to touch the clamp, a sharp click will be heard in the telephone receiver. Then record the reading of the screw. It will be well to repeat this process of setting the

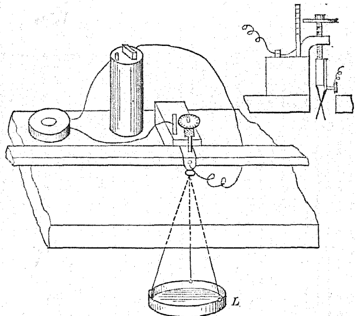


Fig. 52. Measuring the bending of a rod with a screw.

screw for no-load several times so as to be certain that the correct contact point has been got.

When a reading of the magnifying lever or the micrometer screw has been obtained with no load, place in the pan a load of 100 grams and record the new reading. Then remove the load and again get the " no-load " reading, which will probably agree very closely with the first reading.

Now place in the pan a load of 200 grams and record the reading. Remove the load and again determine the " no-load " reading. In this way gradually increase the loads to 500 grams unless the rod shows some permanent deflection.

Record the loads and deflections of the rod in tabular form somewhat as follows:

SUPPORTS 100 cm. APART. WIDTH OF ROD—cm. THICKNESS OF ROD—cm.

LOAD	INDICATOR READINGS		ACTUAL DEFLECTION	DEFLECTION PER 100 G.
	Before Loading	After Loading		
100 g.				
200 g.				
300 g.				
400 g.				
			Average	

From a comparison of the results shown in the last column under "Deflection per 100 g.," *state how the deflection varies with the load.*

NOTE. If metal rods are used with a micrometer screw and heavier loads the results will be more consistent.

Optional experiment. In the same way find the effect of changing the *length* of the rod on the amount of the bending. Set the supports 50 centimeters apart and use loads of 1000 and 2000 grams.

By substituting a rod twice as wide find the effect of changing the *width.* Set the supports 100 centimeters apart and use loads of 400 and 800 grams.

Turn the broad rod up on edge so that the narrow side rests on the supports, which are kept 100 centimeters apart. Use loads of 1000 and 2000 grams and find the effect of changing the *depth.*

By comparing the average deflection per 100 grams obtained in the regular experiment with the averages obtained in these optional experiments, state (*a*) *how the bending decreases when the length is halved,* (*b*) *how the bending decreases when the width is doubled, and* (*c*) *how the bending decreases when the depth is doubled.*

QUESTIONS

1. Why would you expect the results of experiments on the bending of metal rods to be more consistent than those with wood?

2. In these experiments on bending, are you testing the strength or the stiffness of the rods?

3. Do your experiments indicate that Hooke's Law applies to bending?

4. How do you account for the fact that the floors of modern houses are stiffer than those found in old-fashioned houses?

5. When a girder is bent, which part is in a state of tension and which is in a state of compression?

EXPERIMENT 24

ACCELERATED MOTION

How does the distance traversed by a body moving with constant acceleration vary with the time?

Grooved plank according to Duff	Meter stick
Steel ball (1.5″ diam.)	Pepper box with lycopodium powder
Support for one end of incline	Cloth

Introduction. A certain automobile was advertised as being able to start from rest and in 20 seconds to acquire a speed of 60 miles an hour. Assuming that it " picked up " speed at a uniform rate, this would mean that it gained speed at the rate of 3 miles an hour each second. In other words its **acceleration** is 3 miles-per-hour per second, or 4.4 feet-per-second per second. It is quite likely that the automobile did not gain speed at a uniform rate, but actual problems involving non-uniform acceleration are too difficult for us to solve at present.

The first careful study of accelerated motion was made by Galileo early in the seventeenth century by rolling a ball down a long inclined groove. He had great difficulty in measuring short intervals of time. We can now repeat Galileo's experiment with apparatus improved so as to record short equal intervals of time. In this experiment we shall try to find the relation between the *distance* traversed by a ball moving at a uniformly accelerated speed and the *time* which has elapsed during its motion.

We shall use a plank about 4 feet long with a broad groove in the center. When the grooved plank (Fig. 53) is placed

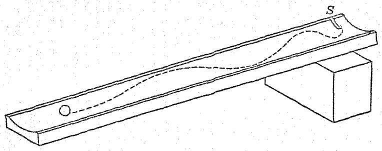


Fig. 53. The ball traces its path on the black board.

horizontally on the table, a steel ball placed on one edge will, when released, oscillate back and forth like a pendulum. Although the swings decrease in amplitude, yet the time of each swing remains constant. When the plank is tilted so that one end is higher than the other, a ball placed at the top in the middle of the groove will roll down, going faster and faster until it reaches the bottom.

Fig. 54. The curve traced.

In this experiment we shall combine this oscillatory motion back and forth across the groove with the accelerated motion down the incline in such a way as to make the oscillatory motion mark off equal intervals of time for the study of the accelerated motion.

Directions. First wipe off the trough with a damp cloth and rub it thoroughly dry, then sprinkle it with lycopodium powder. Tilt the plank with blocks, taking care to keep the under edges at the upper and lower ends exactly horizontal. Place the ball at the top of the groove against the metal strip (S), which serves as a guide until it reaches the middle line. When the ball is released, it goes zigzagging down the groove. If the powder is blown off, we see distinctly the path traced on the black board, somewhat as

shown in figure 54. We have now simply to measure certain distances along the mid-line to understand the relation of *distance* to *time* in a case of accelerated motion.

Record the data and results in tabular form as follows:

Time Intervals (t)	Space Traversed (s)	Distance Covered in Each Time Interval (d)	$\frac{s}{t^2}$	$\frac{d}{2t-1}$
1				
2				
3				
4				
5				

In the second column we record the distances traversed in 1 interval of time, 2 intervals, 3, and so on; that is, AB, AC, AD, AE, etc.

In the third column we record the separate distances covered in the first interval of time, in the second interval, and so on; that is, AB, BC, CD, etc.

Results. From a study of the results given in the fourth column $\left(\frac{s}{t^2}\right)$, *what relation seems to exist between the space s and the time t?* From a study of the results in the last column $\left(\frac{d}{2t-1}\right)$, *what relation seems to exist between the separate distances d and the odd numbers given by the expression* $(2t - 1)$?

Optional experiment. In studying projectiles we have the resultant of two motions, one essentially uniform due to the gun, and the other accelerated. We may conveniently study this problem with Packard's Inclined Plane (Fig. 55).* In this experiment a steel ball

* This was designed by Mr. J. C. Packard of the Brookline (Mass.) High School and is manufactured by the L. E. Knott Apparatus Co., Boston, Mass.

is given a uniform velocity horizontally and at the same time has an accelerated motion downward. The ball in rolling down the inclined plane over a thin sheet of carbon paper traces a curve on the under-

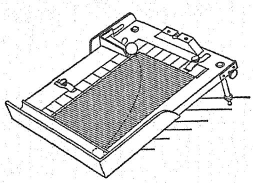


Fig. 55. Apparatus for studying projectiles.

lying cross-section paper. By studying this curve we may arrive at the laws of accelerated motion. Further directions accompany the apparatus.

QUESTIONS AND PROBLEMS

1. What would be the effect of raising the grooved plank so as to make a steeper incline?

2. How would you proceed to determine the time in seconds of one swing of the steel ball, that is, the time for it to swing from the mid-line to the side and back to the mid-line again?

3. In the case of a freely falling body we have accelerated motion in which $\frac{s}{t^2} = 16.1$ where t is expressed in seconds and s in feet. How far would a body fall freely in 3 seconds?

4. If an airplane moving parallel to the ground at 90 miles an hour and 2500 feet above the earth drops a bomb, how far has the airplane moved before the bomb hits?

5. How many seconds (in problem 4) before the airplane is directly over the target must the bomb be released?

EXPERIMENT 25

THE SIMPLE PENDULUM

What is the value of g (the acceleration of gravity) as measured by a simple pendulum?

Ball, lead or iron (about 0.75 inches in diam.)
Linen thread (waxed) or wire (No. 28) about 2 m. long
Stop watch or clock with second hand
Vernier calipers
Meter stick
Support with clamp

Introduction. Everyone is familiar with the pendulum as used in clocks, where it acts as a regulator. It is possible to measure the acceleration of gravity by getting the time of a body falling freely through a known distance, but this method does not give as precise results as can be obtained in experiments with a pendulum. It can be proved mathematically that the fundamental equation for a simple pendulum is

$$t = \pi\sqrt{\frac{l}{g}} \qquad t = \pi\sqrt{\frac{l}{g}}.$$

where t is the time in seconds of a single vibration, l is the length of the pendulum in centimeters, g is the acceleration of gravity in centimeters-per-second per second, and π is 3.14. We can measure t and l directly and π is known, so we may compute the value of g. For this purpose it will be well to use the equation in this form:

$$g = \frac{\pi^2 l}{t^2}.$$

To measure the time t of one vibration, that is, a single swing from one end of its arc to the other, we shall get the time for 50 vibrations and then compute the *period* of the pendulum, or the time that one vibration takes. To determine the length l of a pendulum (where the weight of the supporting thread or

wire is negligible), we measure the distance from the lower edge of the support to the center of the ball, or "bob."

Directions. Attach the bob to a thread about 180 centimeters long and suspend it from the supporting clamp (Fig. 56). A bit of sealing wax will hold the thread to the metal ball. When the pendulum comes to rest, fasten a sheet of paper directly back of the bob so that a vertical black line, which has been ruled on the paper, will indicate the position of rest of the pendulum.

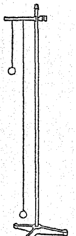


Fig. 56. Two pendulums.

Set the pendulum to swinging through a short arc. As soon as its motion becomes uniform start the stop watch just as the bob passes its position of rest, and at the same time begin counting *zero, one, two, three,* etc., every time the bob passes its position of rest. Stop the watch as the bob passes its position of rest on the *fiftieth* swing.*

Make a second determination of the length of time required for 50 vibrations as before. If the work has been carefully done these two determinations should agree very closely, probably within one second. From the mean value for the time compute the period, or time, of one swing t.

Measure the distance from the supporting clamp to the upper surface of the ball (to 0.1 cm.) and add to this half the diameter as measured with the calipers to the same degree of accuracy. This is to be considered the approximate length (l) of the pendulum. Having thus measured t and l directly and knowing the value of π, compute the value of g.

Repeat the experiment, using a shorter pendulum. If time permits, use a still shorter pendulum.

* If a stop watch is not available, this experiment can be performed with any ordinary clock or watch which is provided with a second hand. It will be well to have two students work together, one to watch and count the pendulum swings and the other to watch the clock and record the hour, minute, and second of the start and finish.

Tabulate your data and results as follows:

Length of Pendulum (l)	Time of 50 Vibrations			Period (t)	g
	Trial 1	Trial 2	Mean		
				Mean =	

Optional experiment. Find whether the time of vibration is affected by varying the *size* or *material* of the bob used, provided the length of the pendulum is not changed.

Also find what effect, if any, a variation of *amplitude* of vibration has upon the time of vibration.

QUESTIONS AND PROBLEMS

1. From a study of the fundamental equation for the pendulum, how would you expect the period of a pendulum to vary with the length?

2. What force keeps a pendulum swinging? Why does a pendulum ever stop vibrating?

3. How does the value which you have determined for g compare with the accepted value? What is the per cent of error?

4. Why does the accepted value for g vary for different localities?

5. What would be the length (in cm.) of a seconds-pendulum, that is, a pendulum whose period is one second?

EXPERIMENT 26

WORK DONE BY A PILE DRIVER*

I. *How does the distance which a nail is driven into a block of wood vary with the distance the hammer drops?*

I. *How does the resistance which the wood offers to the nail vary with the distance which it is driven in?*

Block of iron with two grooved sides (about 4 kg.)	Iron base block
2 Vertical guide rails (about 1 m. long)	Block of wood, pine
	Wire nails (10 cm. long)
	Meter stick

Introduction. When the hammer of a pile driver is lifted, work must be done, which is measured by the product of the weight times the height lifted.

Work done = weight × height

Because of its elevated position the hammer can do work and is said to have **potential energy.** This potential energy is measured in terms of the work which has been done to lift the weight to the raised position.

As the hammer of a pile driver drops, it gradually loses its potential energy and gains more and more of another kind of energy as its speed increases. Just as the hammer hits the pile, its potential energy has all been converted into energy of motion, or **kinetic energy.** It can easily be shown that

$$\text{Kinetic energy} = \frac{Wv^2}{2g}$$

where W = the weight, v = the velocity, and g = the acceleration due to gravity.

* This experiment is based on a similar experiment used by Dr. E. R. Schaeffer of Harvard University and by Prof. Wm. S. Franklin of the Mass. Inst. of Technology.

In this experiment we shall substitute a nail for the pile and a block of wood for the earth (Fig. 57). We shall assume that the kinetic energy of the hammer when it hits the nail is equal to the potential energy of the hammer when it starts to drop. The work done on the nail is equal to the average resistance offered by the wood times the distance it is driven in. We shall assume that the kinetic energy of the hammer is all expended in driving the nail and is therefore equal to the work done on the nail.

In this experiment we shall see the effect of varying the kinetic energy of the hammer and shall learn how the resistance varies as the nail is driven into the wood.

Directions. First drill a short hole in the block of wood just long enough to hold the nail upright. Then measure carefully (to 0.1 cm.) the height of the nail above the wood. Raise the hammer so that its bottom surface is about 40 centimeters above the nail and let it drop. Measure the height of the nail again.

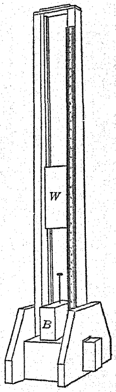


Fig. 57. Model pile driver.

Repeat this operation at least 6 times and each time measure the height of the nail and also the total fall of the hammer (to 0.1 cm.).

From these distances *compute* (1) *the distance which the nail is driven in by each blow,* (2) *the total distance which it has been driven in after each blow, and* (3) *the resistance offered by the wood.*

This resisting force F can be found from the equation:

$$F \times d = W \times h$$

where d is the distance the nail is driven in, W is the weight of the hammer, and h is the distance the hammer drops.

Next start another nail and measure its height above the block. Then raise the hammer 10 centimeters and let it fall

and measure the nail again. Repeat this several times, each time raising the hammer about 10 centimeters higher than before.

Tabulate your data and results as follows:

WEIGHT OF HAMMER —— GRAMS

TOTAL FALL OF HAMMER cm.	HEIGHT OF NAIL ABOVE BLOCK cm.	DISTANCE DRIVEN IN cm.	TOTAL DISTANCE DRIVEN cm.	RESISTING FORCE grams

Results. By examining the tabulated results it will quickly be seen that the nail is not driven into the block an equal

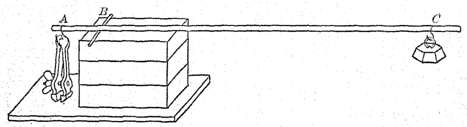


Fig. 58. Force needed to pull out a nail.

distance every time the hammer is dropped a given distance. Since the hammer must have the same kinetic energy, this variation in the distance must be due to the changing resistance of the wood. *This effect may best be shown graphically by plotting the resisting force vertically and the depth of the nail in the wood horizontally.*

In the same way we may show graphically the relation between the total distance the nail is driven in and the various distances of fall of the hammer by *plotting the distances the nail sank vertically and the distance of fall of the hammer horizontally.*

What is the significance of the shape of the curves?

Optional experiment. Arrange a straight lever (Fig. 58) with a small hand vise attached to one end for pulling nails out of a block of wood. Determine the force necessary to pull nails out which have been driven in various distances. Plot a curve to show the relation of the force to the distance which the nail is driven in.

QUESTIONS AND PROBLEMS

1. How do you account for the fact that the resistance offered by the wood is not uniform?

2. How does the velocity of the hammer when it strikes the nail vary with the distance it has fallen?

3. The hammer of a pile driver weighs 300 pounds and is allowed to drop 16 feet.

(*a*) How much potential energy (foot-pounds) did it have at the moment it started to fall?

(*b*) What velocity (feet per second) did it have just before it struck the pile?

(*c*) How much kinetic energy (foot-pounds) did it have when it hit the pile?

HEAT

EXPERIMENT 27

THE FIXED POINTS OF A THERMOMETER

What is the error in the freezing point (0° C.) *and in the boiling point* (100° C.) *of a thermometer?*

Steam boiler with cylindrical top (or a glass flask supported on ring stand)	Thermometer (– 10° to 110° C.)
Bunsen burner	Tumbler or cup
	Clean cracked ice or snow
	Barometer

Introduction. Every household should possess several thermometers, such as one or more room-temperature thermometers, an out-of-doors thermometer, and a clinical or "fever" thermometer. Besides these, many families have several special thermometers, such as a milk thermometer used in pasteurizing milk, an incubator thermometer, a bath thermometer, and the thermometers used on hot-water-heating boilers and on oven doors. In laboratories the so-called chemical thermometer is most commonly used. This consists of a cylindrical glass tube blown or sealed on to the end of a fine-bore glass tube or "stem." The bulb and part of the stem are filled with mercury and the top is sealed after removing the air. A scale is made either on the glass or on a separate strip of metal. For the ordinary Fahrenheit thermometer the melting point of ice is marked 32° and the boiling point of water 212°, and the distance between is divided into 180 equal degrees. On the centigrade scale the ice point is 0° and the boiling point 100°.

The ordinary household thermometer is generally correct within 1 or 2 degrees, although sometimes there is an error of several degrees. It is so important that clinical thermometers

be accurate or at least that the error be known that the U. S. Bureau of Standards tests each year many thousands of these thermometers and furnishes a certificate showing the correction to be added to the different scale readings.

In this experiment we shall test the accuracy of a centigrade chemical thermometer at the 0° point and at the 100° point. These two points are called the **fixed points**, because each of them represents under certain conditions an invariable temperature.

Directions. Fill the boiler about half full of water, screw the chimney or top down firmly, and start heating the water. In lighting a Bunsen burner it is well to turn on the gas and ignite it by holding the lighted match (or gas lighter) 3 or 4 inches above the burner. Sometimes the flame "strikes back" and burns in the tube. In this case turn off the gas and relight it.

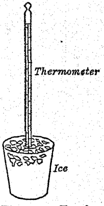


Fig. 59. Testing the 0° C. point.

I. *Freezing point.* Fill a glass tumbler with clean, finely chopped ice (or snow) and pour over it enough water to fill the spaces around the pieces of ice. Put the thermometer bulb down into the melting ice (Fig. 59) so that the top of the mercury column is just visible when it is near the zero mark. After a few minutes, when the mercury has ceased to fall and has apparently come to a definite position, read the thermometer as closely as possible, estimating to tenths of a degree. Adjust your eye so that your line of vision is as nearly as possible at right angles to the thermometer scale. Record this as the freezing point of your thermometer; prefix the plus (+) sign if the reading is above zero or the minus (−) if it is below zero. Thus, + 1.2° or − 0.5° C.

What is the error in the freezing point of your thermometer?

What correction should be added to a reading made on this thermometer near the zero point?

II. *Boiling point.* To test the boiling point the thermometer is exposed to the steam from boiling water. Carefully insert the thermometer in the stopper of the steam boiler (or flask) so that the 100° mark on the scale projects just a little above the stopper (Fig. 60). Let the steam flow around the bulb and stem for several minutes until the thermometer has come to a fixed reading. Then read and record its position and also the barometric height.

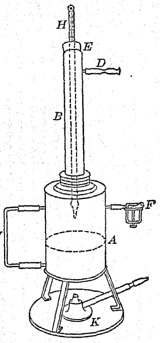


Fig. 60. Testing the 100° C. point.

When the barometer stands at 76 centimeters, the boiling point of water is 100° C. At higher pressures the temperature of steam is higher, and at lower pressures it is lower. Careful experiments show that a change of one centimeter in the height of the barometer causes a change of approximately 0.37° C. in the boiling point. For example, if the barometer reads 74.5 centimeters, then the boiling point of water is

$$100 - (1.5 \times 0.37) = 99.4° \text{ C.}$$

Calculate from the barometric pressure the true boiling point at the time of your experiment.

Compute the error in the boiling point of your thermometer.

What correction should be added to a reading on this thermometer made near the 100° mark?

Record your data and results neatly in tabular form.

Optional experiments. (*a*) To determine *how much the pressure of steam must be increased to raise its temperature 1° C.*, attach a pressure gauge to the boiler, as shown in figure 61. When the steam is escaping freely into the air at A, the mercury * in the gauge G reads at the

* If water is used in the gauge instead of mercury, a taller U-tube must be used or a straight tube dipping into a deep jar of water.

same level in each arm. If we gradually close the exit A by screwing up the pinchcock, the pressure gauge will show a difference of levels. When this difference amounts to 6 or 8 centimeters and has become fairly steady for 2 or 3 minutes, read *very carefully* the thermometer. Then close the pinchcock still further until the difference in level amounts to 8 or 10 centimeters and read again. Make a third trial by loosening the pinchcock a bit. From each of these sets of readings compute the pressure needed to increase the temperature of steam 1° C. Compare the mean of these values with the accepted value given in Part II.

(*b*) **Test a thermometer used at home.** The freezing point (32° F.) is readily tested as described in Part I. Higher points may be tested by placing the thermometer in warm water at about 25° C. and comparing its reading with that of a good laboratory thermometer. Points below the freezing point may be tested by placing both the thermometers in a freezing mixture of ice (or snow), salt, and water.*

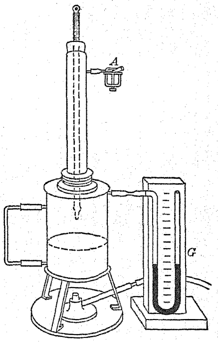


Fig. 61. **Effect of pressure on the boiling point.**

QUESTIONS AND PROBLEMS

1. Experiments show that an increase of pressure *lowers* the freezing point of water 0.0072° C. per atmosphere. Why do we not correct the reading of the thermometer in melting ice for barometric pressure?

2. If the freezing point of a thermometer is tested immediately *after* its boiling point, it will not indicate the same reading as it showed when tested first. Explain.

3. If the boiling point of a thermometer is tested with the stem in the air and only the bulb surrounded by steam, the reading will not be the same as when both are in steam. Explain.

* For further directions about the use and testing of thermometers, consult "Measurements for the Household," *Circular No. 55 of Bureau of Standards.* U. S. Government Printing Office, Washington, D. C.

4. How could you estimate the altitude of a place if you had an accurate thermometer?

5. On a certain day a standard thermometer was found to read in steam 98.5° C. What was the pressure?

6. Find the boiling point of water when the barometric pressure is 77 centimeters.

EXPERIMENT 23

LINEAR EXPANSION OF A SOLID

How much does one centimeter of aluminum (or brass) expand when heated one degree centigrade?

Linear expansion apparatus (Hall or Cowen form)	Thermometer
	Barometer
Steam boiler and burner	Vernier calipers
Meter stick	

Introduction. It is a well-known fact that nearly every solid expands when heated and contracts when cooled. This is made use of in setting steel tires on locomotive wheels and on carriage wheels and has to be allowed for by expansion joints in steel bridges and railway tracks. The exact amount of this expansion depends on *three factors:* (1) the material, (2) the length of the object heated, and (3) its change in temperature. This may be expressed as an equation, thus:

$$e = kl(t' - t)$$

where e is the change in length, l the initial length, t' the temperature when hot, and t the temperature when cold. The factor k is the expansion of a unit length for 1 degree rise in temperature and is called the **coefficient of linear expansion.** This factor is a very small fraction and varies with different substances.

In this experiment we shall measure the expansion of a given length of metal tubing when heated from the temperature of the room to that of steam. Then we shall compute the expansion per unit length for one degree centigrade.

Directions. Since the amount which a solid expands is exceedingly small, it is difficult to measure it with great precision. One of the many forms of apparatus used to measure this slight expansion employs a lever to magnify the actual expansion, as shown in figure 62.* The metal tube is heated by passing steam through it. One end of the tube is made fast with a pin P, and the other end, as the tube expands, turns a bent lever BCD about the point A. The expansion of the tube is magnified as many times as the short arm AB of the lever is contained in the long arm AD. Therefore, to get the actual expansion we have merely to divide the rise of the pointer D on the scale by the magnifying power of the lever.

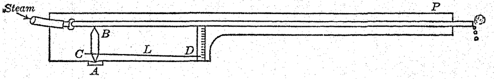


Fig. 62. Hall's expansion apparatus.

The length of the tube between the fixed point P and the point B, where the bent lever rests against the tube, can easily be measured to three significant figures with an ordinary meter stick. The short arm of the bent lever can be measured with sufficient precision by means of vernier calipers. If the tube has been in the room for several hours, it may be assumed to be at room temperature. (A more accurate method is to run water of a known temperature through the tube.) Read very carefully the position of the pointer on the scale, estimating to tenths of a millimeter.

Then connect the tube by rubber tubing with the steam boiler and run steam through it until there is no further movement of the pointer. While the steam is still flowing read again as carefully as before the position of the pointer and compute the rise of the pointer. All linear measurements should be made in the same units, for example, all in centimeters.

* This form of apparatus was designed by Mr. C. M. Hall of the Springfield (Mass.) Central High School and is made by the Cambridge Botanical Supply Co., Waverley, Mass.

The temperature of the steam may best be computed from the barometric pressure as explained in Experiment 27.

Compute the actual expansion, also the expansion of a unit length (1 centimeter) per degree centigrade, that is, *the coefficient of linear expansion of the metal used.*

Record all your data and results in tabular form.

Optional experiments. A more accurate and more delicate form of apparatus* for this experiment is shown in figure 63. In this apparatus the expansion is measured by allowing the tube T to rest on a needle N, which in turn rests on roller bearings BB. The rotation of the needle is measured on a circular scale by a pointer. Evidently if the needle makes one complete revolution, the tube has expanded

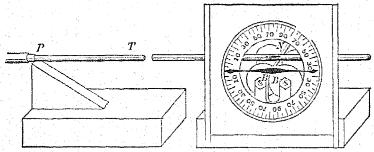


Fig. 63. Cowen's expansion apparatus.

a distance equal to the circumference of the needle; and if it turns less than a complete revolution, the tube has expanded the corresponding fraction of the circumference of the needle. The diameter of the needle can be measured with great precision by means of a micrometer caliper.

A third form of apparatus consists of a metal rod which is inclosed in a tubular jacket. The expansion is measured by means of a micrometer screw and the rod is heated by passing steam through the outside jacket. To determine just when the screw touches the rod, connect a dry cell and telephone receiver in series with the rod and the micrometer screw so that the electric circuit is closed (as indicated by the click heard in the receiver) when the screw just touches the rod.

*This form of apparatus was designed by Mr. G. A. Cowen of the West Roxbury High School, Boston, and is made by the L. E. Knott Apparatus Co., Boston.

QUESTIONS AND PROBLEMS

1. What is the least accurate quantity which you have measured in this experiment? With what accuracy have you measured it?

2. Why was it not necessary to measure the length more closely than to millimeters?

3. If you know the coefficient of expansion per degree centigrade, how would you compute the coefficient per degree Fahrenheit?

4. What allowance (expressed in inches) must be made in an iron pipe 30 feet long for a change in temperature from 40° F. to 225° F.? (The coefficient of linear expansion of iron is 0.000011 per degree centigrade.)

5. A radio station has an aerial which is a copper wire 125 feet long at − 10° C. What will be its length when the temperature is 95° F.? (Coefficient of linear expansion for copper = 0.000017 per degree centigrade.)

EXPERIMENT 29

CUBICAL EXPANSION OF AIR

What fraction of its volume at 0° C. does a certain quantity of air expand when heated 1° C. under constant pressure?

Charles' Law tube with dry air and short thread of mercury	Boiler with top
Small rubber bands	Bunsen burner
Thermometer	Pail or jar of cracked ice (or snow)

Meter stick

Introduction. Liquids when heated expand more than solids; for example, the mercury in a thermometer expands more than the glass bulb. Gases expand much more than liquids and, what is more remarkable, *all gases expand at about the same rate.* The ratio between the increase in volume per degree and the volume at 0° C. is called the **volume coefficient of expansion.** Thus, if V_{100} and V_0 represent the volumes at 100° C. and 0° C., respectively, then the volume coefficient K is given by the equation

$$K = \frac{V_{100} - V_0}{100\, V_0}.$$

The expansion of gas when heated is what makes the bread dough "rise" and forms the little holes in the bread. Here it is the bubbles of gas (CO_2) formed by the yeast or baking powder which expand. Why does cake dough sometimes "fall" if it is removed from the oven too soon?

If a certain quantity of gas is heated in a closed vessel so that the volume is kept constant, the pressure which the gas exerts against the walls of the vessel increases as the temperature rises. This is really what makes the gas engine work. A mixture of gas and air is exploded in the closed end of the cylinder producing a very high temperature and a corresponding increase in pressure. It is this pressure which drives the piston. The ratio between the increase in pressure per degree and the pressure which a gas exerts at 0° C. is called the **pressure coefficient of expansion of the gas.** Experiments show that this pressure coefficient of expansion is the same for all gases and is equal to the volume coefficient of expansion. Thus we see that this coefficient is a very important factor in all gas problems.

Fig. 64. An air thermometer.

Directions. In this experiment the apparatus is very simple. It consists of a thick-walled glass tube (about 50 cm. long) with a uniform bore of about 1.5 millimeters diameter. One end is closed. The tube contains a column of dry air about 20 to 25 centimeters long which is confined by a thread of mercury 2 or 3 centimeters long, as shown in figure 64. The distance *AM* from the closed end of the bore up to the mercury represents the volume of the air. (The volume of the air is measured in terms of the volume of a unit length of the tube.) This apparatus forms a simple constant-pressure air thermometer and must be handled with care so as not to break the thread of mercury into two or more sections.

Stand the air tube upright, closed end down, in a pail or jar of cracked ice (or snow). Pack the crushed ice closely about

the tube so that the air column is covered with ice up to the mercury. Tap the tube with a pencil, and when the mercury index comes to a position of rest, mark the position of the lower end of the mercury with a small rubber band* around the tube. Make the lower edge of the band coincide with the lower end of the mercury index.

Remove the tube from the ice, lay it alongside the meter stick, and measure the distance from the closed end of the bore to the rubber band. (Allow as best you can for the fact that the bore is not quite uniform very near the closed end.) This represents the volume of the air at 0° C.

Now put the air tube into the top of the steam boiler in such a way as to surround the air column with steam. When the mercury ceases to rise in the tube, again mark the position of the lower end of the mercury with the rubber band. Remove the tube from the boiler and measure the length of the air column at the temperature of steam.

Read the barometer and compute the temperature of the steam for the observed barometric pressure as in Experiment 27, II.

Record your data and results in tabular form.

Results. Compute

(*a*) *the expansion of the air;*

(*b*) *the rise in temperature* (from ice to steam);

(*c*) *the expansion per degree rise in temperature;*

(*d*) *the expansion of one centimeter per degree.*

This last result is the coefficient of cubical expansion of air.

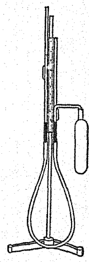


Fig. 65. Measuring pressure of air in bulb.

Optional experiment. Determine the **pressure coefficient of expansion** of air. Attach a glass bulb to a mercury pressure gauge made of two glass tubes connected by a rubber tube (Fig. 65). Make a scratch on the arm of the manometer to which the bulb is attached. Place the air bulb first in

* These bands are easily made by cutting slices off the end of a "pure gum" tube with scissors.

melting ice (or snow) and adjust the manometer arms so that the top of the mercury is just opposite the scratch. Read the mercury levels in each arm of the manometer and record the barometric pressure. Put the air bulb in the steam generator so that it will be surrounded with steam and again adjust the levels until the mercury is at the scratch. Read the mercury levels. *Before the air bulb is allowed to cool, lower the open arm of the manometer to keep the mercury from being drawn over into the bulb.* From these data compute the ratio between the increase in pressure per degree and the pressure which the gas exerts at 0° C., that is, *the pressure coefficient of gases.*

QUESTIONS

1. How would the expansion of the glass tube affect the result in this experiment?

2. What was the pressure of the confined air throughout the experiment?

3. Express the volume coefficient of expansion which you obtained as a common fraction whose numerator is 1. What is the denominator of this fraction?

4. Why is it necessary to keep the air in these tubes *very dry?*

5. Why is it essential to take special care in cleaning the glass tube and in purifying the mercury?

6. How could you test a capillary tube as to the uniformity of its bore?

EXPERIMENT 30

HEAT INSULATORS* — THERMOS BOTTLE

How do various heat insulating materials used commercially compare in their effectiveness?

Several cylindrical vessels of the same shape and capacity, such as the copper dippers used with the steam boilers
Cork stoppers to fit
Thermometer
Insulating jackets to fit around the dippers (made of such materials as asbestos, hair felt, crumpled newspaper, etc.)
Supply of boiling water
Supply of ice water

Introduction. It is a well-known fact that some materials conduct heat better than others. Thus the metals, especially

*This experiment is based on a similar experiment (No. 71) in Ahrens, Harley and Burns' *A Practical Physics Manual.*

silver and copper, are good conductors, while glass, porcelain, and dry air are such extremely poor conductors that they are called **heat insulators.** Since heat passes more readily through some substances than through others, it will be useful to know the heat-insulating values of various materials in common use, because such knowledge makes it possible to save much heat which would otherwise be lost. Thus hot-water, steam, and hot-air pipes are often covered with insulating materials, such as asbestos or hair felt, to reduce the loss of heat from them. The fireless cooker, the refrigerator, and the thermos bottle all depend for their effectiveness on their heat-insulating walls.

Directions.* First see that each dipper is provided with a closely fitting stopper to prevent a loss of heat by radiation

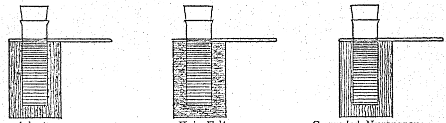


Fig. 66. Insulated dippers

and that all the dippers but one are provided with insulating jackets (Fig. 66). Have ready a supply of boiling water (teakettle) to fill all the dippers at once. Pour into each enough hot water to fill it to within an inch of the top. Then take and record the temperature of each and the time. Insert the stopper as soon as the temperature is taken. Take the temperature every 10 minutes for half an hour.

Repeat the experiment using ice water in place of hot water. Tabulate your data.

Results. To show the cooling of the hot water graphically, plot the time horizontally and the temperature vertically. In

*With large classes it will probably be advisable to furnish each pupil with but one dipper and then to let each compare his results with those of the other members of the class using other insulators.

the same way the warming of the ice water may be represented graphically.

(a) *Compute the rate of cooling, that is, the average temperature drop per minute.*

(b) *Compute the rate of absorbing heat, that is, the average temperature rise per minute.*

(c) *Why is the rate of cooling greater than the rate of warming?*

(d) *Which insulating material do you consider the best? Why?*

Optional experiment. Repeat this experiment with several brands of thermos bottles, extending the test over several hours. Draw a cross-sectional diagram of the most effective type of bottle and explain why it is better than any of the insulators used in the regular experiment.

QUESTIONS

1. In comparing heat insulators why should we use the same thickness of each material?

2. Experiments show that very soft wood is about four times as good a heat-insulator as hard wood. Explain.

3. Why is a fur coat very much warmer if the fur is on the inside?

4. In baking in an ordinary oven more than 90 per cent of the heat is wasted. Explain how the walls should be made.

5. Why should the walls of a refrigerator contain heat-insulating material?

EXPERIMENT 31

SPECIFIC HEAT OF A METAL

How many calories does 1 gram of a metal give out in cooling 1° C.?

Metal ball, cylinder, or shot (such as aluminum, copper, or lead)	Thermometer
	Platform or beam balance
	Set of weights
Boiler and burner	Cylindrical graduate (200 cm.^{3})

Calorimeter, preferably double-walled

Introduction. Thus far we have been concerned with changes in temperature and these we could measure with a thermometer.

But very many important problems, such as the heat value of fuels, involve the *measurement of heat*. It will readily be seen that it takes *twice* as much heat to raise the temperature of a pound of water *ten* degrees as to raise a pound of water *five* degrees; and that it takes *twice* as much heat to raise the temperature of *two* pounds of water one degree as to raise *one* pound of water one degree. In short, to measure heat we must know the weight of the material heated and the number of degrees through which it is heated.

For engineering purposes in this country and in other English-speaking countries, the **heat unit** is the *British thermal unit* (B. t. u.), which is the amount of heat required to warm 1 pound of water 1 degree Fahrenheit. The heat unit that is used in almost all scientific work, however, is the *calorie*. This is the amount of heat required to warm 1 gram of water 1 degree centigrade. For example, 1 cubic foot of illuminating gas will furnish about 600 British thermal units, and a shredded wheat biscuit will supply us with energy equivalent to about 100 calories.

Different substances vary greatly in the amount of heat required to produce the same change in temperature. For example, one British thermal unit will raise the temperature of one pound of iron about 9 degrees Fahrenheit. In other words, it takes 0.11 British thermal units to raise 1 pound of iron 1 degree Fahrenheit and so the specific heat of iron is said to be 0.11. We can easily show that the numerical value for specific heat is the same whether we use British thermal units or calories.

Method. To measure heat we often use the **method of mixtures.** This method assumes that we can mix a hot substance with a cold substance without any loss of heat in the process. It also assumes that the heat units given out by the hot body in cooling equal the heat units absorbed by the cold body in being warmed. In carrying this out in the laboratory we use a **calorimeter**, which is usually a copper or brass vessel nickel-

plated to prevent radiation. Sometimes it is provided with a double wall having an air space between. In all experiments involving heat measurements the temperatures must be taken with great care (estimate to tenths of a degree) and any liquids used must be thoroughly stirred before taking the temperature.

The principle involved in this experiment is very simple. A hot mass of metal is dropped into cold water and the water absorbs the heat given out by the cooling metal. In other words,

$$\textit{Heat given out} = \textit{Heat taken in}$$
$$m(t_m - t_{mix})X = w(t_{mix} - t_w)1$$

where m = weight of metal, t_m = temperature of metal, X = specific heat of metal, w = weight of water, t_{mix} = temperature of mixture, and t_w = temperature of cold water.

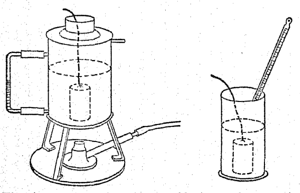


Fig. 67. Measuring the specific heat of a metal.

But it must also be remembered that the calorimeter which holds the water absorbs heat. Experiments show that brass (the metal commonly used for the calorimeter) absorbs about one tenth as much heat as the same weight of water. Therefore one tenth the weight of the calorimeter, called the **water equivalent** of the calorimeter, is to be added to the weight of water used.

Directions. It is convenient to have the metal* in the form of a ball or cylinder which can be heated directly in the water of the boiler (Fig. 67). Weigh the metal (to 0.1 g.) and then put it into the boiler to heat.

In the meantime measure out in a cylindrical graduate a

*If the metal for this experiment is finely divided shot, it may be heated in a dipper set in a boiler and its temperature can be determined by placing a thermometer in the midst of the shot.

certain quantity of cold water, about 200 cubic centimeters at from 5° to 10° C. Record the weight of water used, considering 1 cubic centimeter of water as equal to 1 gram. Also record the weight of the calorimeter (inner cup, if used).

When the metal has reached the temperature of the boiling water, which is to be computed from the barometric reading, read carefully the temperature of the cold water and by means of a thread quickly lift the metal out of the boiler and put it in the cold water. Stir the water and take its final temperature as soon as it becomes constant.

These data should be recorded in tabular form:

Weight of metal (m)	g.
Weight of cold water (w)	g.
Weight of calorimeter (c)	g.
Temperature of metal (t_m)	° C.
Temperature of cold water (t_w)	° C.
Temperature of water and metal (t_{mix})	° C.

Computations. From these facts calculate the following results:

Water equivalent of calorimeter $(0.1\ c)$
Weight of water and water equivalent of cal. $(w + 0.1\ c)$
Rise of temperature of water and calorimeter $(t_{mix} - t_w)$
Calories absorbed by water and calorimeter
Drop in temperature of metal $(t_m - t_{mix})$

Let X be the specific heat of the metal, then the calories given out by the metal in cooling are $m(t_m - t_{mix})X$. The heat equation may be stated thus:

$$\textit{Heat given out} = \textit{Heat taken in}$$
$$m(t_m - t_{mix})X = (w + 0.1\ c)(t_{mix} - t_w)$$
$$\therefore X = \text{——}\ \text{cal.}$$

Specific heat of —— *is found to be* —— *calories.*

The value for —— given in the table in the Appendix is —— calories.

Optional experiments. It will be noted that the equation for the fundamental principle of this experiment contains seven quantities, and therefore if any six of them are determined experimentally, the seventh one may be computed.

Use this method to find the temperature of a red-hot iron ball. Suspend an iron ball on an iron wire in a Bunsen flame until it is red-hot. Then plunge it into cold water in a calorimeter. Compute the number of calories received by the water and calorimeter. Knowing the weight of the ball and assuming the specific heat (see Appendix), compute the temperature of the red-hot ball. What are the sources of error which render this method only approximate?

The same method can be used to determine the specific heat of a liquid by mixing it with a metal of known specific heat. Determine the specific heat of kerosene in this way.

QUESTIONS AND PROBLEMS

1. Why is it advisable in this experiment to begin with the water at a temperature about as much *below* the room temperature as the final temperature of the mixture is *above* the room temperature?

2. If the metal is finely divided, such as lead shot, why is the temperature of the hot metal in the dipper always 1 or 2 degrees below the temperature of the steam outside the dipper?

3. Why is it essential to transfer the metal to the calorimeter quickly?

4. Given the specific heat of a calorimeter and its weight, how would you compute its water equivalent?

5. How many British thermal units are given out by 2 quarts of water in a hot-water bag in cooling from 200° to 100° F.?

6. How many British thermal units are required to heat a 2-pound flatiron from 65° to 350° F.?

EXPERIMENT 32

COOLING THROUGH THE MELTING POINT

How does the temperature of a liquid change as it cools and changes into the solid state?

Acetamide or naphthalene	Boiler
Test tube (about 2 × 10 cm.) with cork to fit	Bunsen burner
Clamp to support test tube	Millimeter cross-section paper
Thermometer	Clock or stop watch

Introduction. We may study the rate of cooling of a hot substance by observing at regular intervals its temperature as it cools, and then may represent the results graphically by plotting the temperatures vertically and the time horizontally. If the material tested cools very slowly at a uniform rate, the cooling curve is a straight line with a very gentle slope; but if it cools rapidly, the curve has a steep slope. If it cools at first rapidly, and then gradually cools more and more slowly, the curve is not a straight line but curves with its concave side upward. In this experiment we shall observe a decided change in the shape of the cooling curve during the process of change from liquid to solid, which indicates a new source of heat. A convenient substance to study through these temperature changes is acetamide.

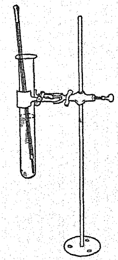


Fig. 68. How fast does the liquid cool?

Directions. Fill a test tube about half full of the crystals of acetamide and heat the tube in the water of the boiler until the acetamide has melted and reached a temperature between 95° and 100° C. Then remove the test tube from the water and clamp it in such a position that the thermometer is easily read as the liquid cools (Fig. 68).

Without disturbing the liquid or the thermometer in any way, read and record the temperature (estimating to one tenth of a degree) every half minute. Note when the crystals begin to form in the liquid and take the observations every minute until the solid has cooled to about 50° C.

Results. To show graphically these changes that occur during the process of cooling, we plot the results on cross-section paper, representing *temperatures* by vertical distances

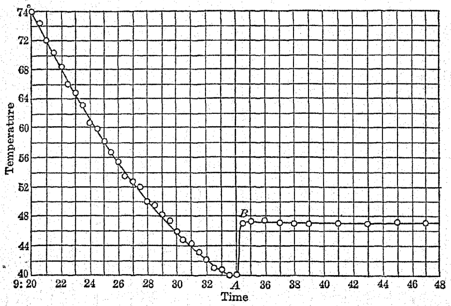


Fig. 68A. Cooling curve of "hypo."

(1 mm. for 1°) and *times* by horizontal distances (4 mm. for 1 min.). Begin both the time scale and the temperature scale at the lower left-hand corner. Make a tiny circle or cross to indicate the position of each observation and then draw a line passing along the course indicated by the several points located on the paper, as shown in figure 68A.

Study this curve carefully so as to be able to answer such questions as the following:

(*a*) *What portion of the curve represents the cooling of the substance in the liquid state?*

(*b*) *What portion of the curve represents the condition during the process of crystallization?*

(*c*) *What portion of the curve represents the cooling of the substance in the solid state?*

(*d*) *Is there any part of the curve which indicates "subcooling"?*

(*e*) *What would you consider the freezing point of the substance used?*

Optional experiment. In the same way study the cooling of naphthalene or of sodium thiosulfate (photographer's "hypo").

QUESTIONS

1. Why does the temperature of a solidifying liquid remain nearly constant during the process of solidification?

2. Why does a substance cool more rapidly in the liquid state than in the solid state?

3. Why does a solid cool more slowly as it approaches room temperature?

4. Why was it desirable that the liquid remain at rest while cooling?

5. What is a safe method of procedure in removing the thermometer from the solidified substance?

Lee.

EXPERIMENT 33

THE HEAT OF MELTING FOR ICE

How many calories are required to melt one gram of ice?

Clean ice	Platform or beam balance and set of weights
Calorimeter	Supply of hot water (tea kettle)
Thermometer	
Cloth or paper towel	

Introduction. It is a well-known fact that ice or snow absorbs heat in the process of melting. In the ice-cream freezer the broken ice in the outer bucket cools the cream to the freezing point, while the salt and ice together produce a still lower temperature, which freezes the cream. In the household refrigerator the melting of the ice is necessary to

cool the food to the proper temperature for preservation. A really good refrigerator has heat-insulating walls, so that most of the heat used in melting the ice comes from the food and air inside the box and very little is conducted through the walls.

But how much heat (B. t. u.) is required to melt a pound of ice? How many calories are required to melt one gram of ice at 0° C. into water at 0° C.? To determine this is the object of our experiment.

In attacking this problem we shall use the method of mixtures. The heat units given out by a certain amount of warm water in cooling will be used *first* to melt the ice and *second* to raise the water which is formed from zero to the final temperature. If each gram of ice in changing from ice at 0° C. to water at 0° C. requires X calories, then i grams of ice would require iX calories. But after the ice is melted it becomes i grams of water at 0° C., and this water is raised to the final temperature t', which requires it' calories in addition. This heat is supplied by w grams of water and by c grams of calorimeter (whose specific heat is about 0.1) in cooling from the initial temperature t to the final temperature t'. This heat is equal to $(w + 0.1\,c)(t - t')$ calories. We can now make an equation as follows:

Heat absorbed by ice = heat given out by water and calorimeter

$$iX + it = (w + 0.1\,c)(t - t')$$

and from this we can solve for X, the heat of melting for ice.

Directions. First weigh the calorimeter (inner cup) empty and then with about 300 grams of warm water (about 45° C.). Break or grind up enough clean ice to fill a 150-cubic-centimeter glass with pieces less than 2 centimeters in diameter. Stir the water in the calorimeter thoroughly and determine its temperature to a tenth of a degree. At once add the ice quickly, taking care to wipe each piece on the cloth (why?) and not to spatter the water. Stir the water continually, and when the temperature of the water has cooled to 10° C. or lower, stop adding

ice. Just as soon as the last piece melts, read the temperature again with great precision.

To find out how much ice has been used, weigh the calorimeter with its water and melted ice.

We now have the following data:

Weight of calorimeter (c)	g.
Weight of calorimeter + water	g.
Weight of water (w)	g.
Initial temperature of water (t)	° C.
Final temperature of water (t')	° C.
Weight of calorimeter + water + ice	g.
Weight of ice (i)	g.

Computation. We may now substitute in the heat equation given above the quantities which have been determined experimentally, and solve for X, that is, *the number of calories required to melt one gram of ice at 0° C. to water at 0° C.*

Optional experiment. Study your refrigerator at home. Make a cross-section diagram to show the convection currents of air. Measure *the inside volume, the room temperature, the coldest inside temperature, the warmest inside temperature, and the weight of ice melted per hour.* Remember that a good refrigerator maintains a low inside temperature (from 45° to 65° F.) and a low rate of ice-consumption (about 1.5 lbs. per hour). Compare your refrigerator with those of your neighbors in these two respects.

QUESTIONS AND PROBLEMS

1. Why is the heat used to change a solid to a liquid without change in temperature sometimes called latent (hidden) heat?

2. What becomes of the heat energy used in melting ice?

3. If the accepted value of heat for melting ice is 80 calories per gram, compute the percentage of error in your experimental result.

4. How many grams of ice are needed to cool a quart (1 liter = 1.06 quarts) of lemonade (specific heat = 1) from 80° to 40° F.? Assume the ice is put directly into the lemonade.

5. A certain ice box melts 35 pounds of ice in 24 hours and the temperature of the waste water is 42° F. Compute the total heat units (B. t. u.) required to melt the ice and raise the temperature of the waste water. Assume the heat of melting of ice is 144 B. t. u.

EXPERIMENT 34

THE HEAT OF CONDENSATION OF STEAM

How many calories are given out when 1 gram of steam at 100° *C. condenses into water at* 100° *C.?*

Boiler and burner	Thermometer
Condensed-steam trap	Platform or beam balance
Calorimeter	Set of weights

Introduction. Suppose we heat a certain quantity of water from 0° to 100° C. and note the time required. Then suppose we boil all the water away and note the time required for this process. We shall find that it takes about five times as long to change all the water into steam as it takes to heat the water from 0° to 100° C. Presumably the water has been receiving heat at about the same rate all the time, and since the water did not get hotter than 100° C., we must conclude that it takes about five times as much heat to change it to steam as it took in when heated from 0° to 100° C. This heat which is absorbed in the process of changing water into steam is called the **heat of vaporization**, or the latent heat of steam.

When the steam condenses back to water, this latent (hidden) heat of the steam is given out. It is this heat of condensation of steam which is made use of in steam heating. Steam is generated in a boiler, is then piped to the place where heat is wanted, and is there condensed, giving back all the heat which was absorbed in vaporizing it.

In order to determine how many calories are given out when one gram of steam at 100° C. condenses into water at 100° C., we shall run some "live steam" into cold water and observe the rise in temperature. By weighing the calorimeter and water after running in the steam we shall be able to determine the weight of steam used. Thus it will be seen that we again use the method of mixtures, making an equation between the *heat*

units absorbed by the calorimeter and cold water and the *heat units given out* by the steam in condensing and by the water formed by the condensed steam in cooling from 100° C. to the final temperature of the mixture. The success of this experiment depends very much on careful weighing (to 0.1 g.) and on the careful reading of the temperatures (to 0.1° C.).

Directions. Fill the boiler half full of water and start heating. Then fill the calorimeter, whose weight has already been determined, two thirds full of cold water (about 5° C.),* and determine the weight of the water with great precision. Set up a book or wooden screen between the boiler and the calorimeter and place a thermometer in the water.

As soon as the water in the boiler begins to boil, attach the trap to the delivery tube, as shown in figure 69, to catch any steam which condenses in the tube. Stir the water in the calorimeter with the thermometer and read its temperature.

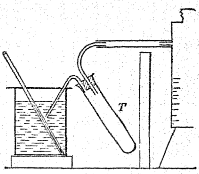


Fig. 69. Heating water with "live steam."

Then quickly put the delivery tube into the water so that its end projects under water about 2 centimeters. Continue to stir the water slowly until it gets to a temperature about as much above that of the room as the initial temperature was below it. Remove the delivery tube from the calorimeter and after stirring read the highest temperature which the water reaches.

Finally, as soon as convenient, weigh with great care (to 0.1 g.) the calorimeter, water, and condensed steam and compute the weight of the steam used. The temperature of the steam can best be computed from the barometric pressure.

* If necessary cool the water with bits of ice, but be sure that no ice remains unmelted when the temperature is taken.

Record all your observations as soon as they are taken in tabular form somewhat as follows:

TRIALS	I	II
Weight of calorimeter (c)	g.	g.
Weight of calorimeter + water	g.	g.
Weight of water (w)	g.	g.
Initial temperature of water (t)	° C.	° C.
Final temperature of water (t')	° C.	° C.
Weight of cal. + water + steam	g.	g.
Weight of condensed steam (s)	g.	g.
Barometric pressure	cm.	cm.

Computations.

(*a*) *What was the temperature of the steam?* (See Experiment 27, Part II.)

(*b*) *What is the water equivalent of the calorimeter?* $(0.1\,c)$

(*c*) *How many calories have the calorimeter and water absorbed?* $(w + 0.1\,c)(t' - t)$

(*d*) *How many calories did s grams of condensed steam give out in cooling, say from 100° C. to t′ C?* $s(100 - t')$

(*e*) Assuming that each gram of steam in condensing gave out X calories, then s grams would give out sX calories.

(*f*) Now state in the form of an equation the heat given out and the heat absorbed. That is, substitute in the following equation:

$$\textit{Heat given out} = \textit{Heat absorbed}$$

$$sX + s(100 - t') = (w + 0.1\,c)(t' - t)$$

Solve for X, which is the heat given up by 1 gram of steam in changing into water.

(*g*) The accepted value for the latent heat of steam is 540 calories per gram.

*Compute your per cent of error.**

*With reasonable care it is not difficult to get a result in this experiment within 5 per cent.

If time permits, make a second trial.

Optional experiment. An approximate value of the latent heat of steam can be obtained by getting the time necessary to bring ice-cold water to the boiling point and the time needed to boil it all away, as described in the Introduction of this experiment. Try it, using about 100 grams of water in a 300-cubic-centimeter pyrex beaker.

QUESTIONS AND PROBLEMS

1. What causes the loud cracking noise when the steam is run into the cold water?

2. Sometimes the water rushes back into the trap for condensed steam. What is the cause?

3. Why is a steam radiator smaller than a hot-water radiator for the same room?

4. How many calories will be required to raise 1 kilogram of water at 20° C. to 100° C. and convert it all into steam?

5. How many B. t. u. will be supplied by condensing 10 pounds of steam at 212° F. and cooling it to 68° F.? Assume the latent heat of steam is 972 B. t. u. per pound.

EXPERIMENT 35

DEW POINT AND RELATIVE HUMIDITY

I. *At what temperature is the air of the room saturated with the moisture present?*

II. *What is the relative humidity of the air of the room?*

Calorimeter with bright exterior surface	Tumbler of water at room temperature
Thermometer	Salt and ice

Introduction. The air out of doors always contains some moisture even though not visible as rain or snow. It is this moisture which makes a pitcher of ice water "sweat" during a hot day in summer and makes water drip from pipes through which cool water is flowing.

It is necessary to determine the humidity of the air in greenhouses because the plants cannot thrive if the air becomes too dry. It is well known that the air in our homes often contains less water vapor than a desert region. This too dry air rapidly absorbs moisture from the skin, nose, and throat, preparing the way for the attack of disease germs. This excessively dry air in our houses, it is said, also leads to a waste of fuel which is estimated at from 10 to 25 per cent. This is because a more humid atmosphere would diminish the cooling effect produced by the rapid evaporation of the perspiration from the skin and so would make us feel more comfortable at 65° F. than we do now at 70° F. To correct this condition the air in hospitals, public buildings, textile factories, and even in a few private dwellings is being humidified artificially.

How shall we measure the humidity of the atmosphere? It is possible to determine the number of grams of water vapor in one cubic meter of air; this is the absolute humidity of the atmosphere at a given temperature. Experiments show that the amount of vapor which may be present without precipitation (rain or snow) varies with the temperature and that a rise in temperature increases rapidly the quantity of vapor required to saturate the air. This is clearly shown in Table VIII in the Appendix.

If the air is gradually cooled, a temperature will be reached at which the vapor present will saturate the air; if the air is still further cooled, the vapor will condense and be deposited. This temperature at which the air becomes saturated is called the **dew point**. Knowing the dew point we may readily compute the **relative humidity** of the air, that is, the ratio between the amount of moisture actually in the air and the amount which would be present if the air were completely saturated. For example, suppose the temperature is 20° C. and the dew point is found to be 10° C. What is the relative humidity? From the humidity tables we find that a cubic meter of saturated air contains at 10° C. 9.36 grams of water and at 20° C.

17.15 grams. Therefore the air is $\frac{9.36}{17.15}$, or 54 per cent, saturated.*

Directions. See that the outside of the can is bright. Half fill the vessel with water at room temperature. Gradually cool this water by adding chips of ice (and salt if needed) and stir constantly with the thermometer. Watch carefully the lower part of the can for the first signs of moisture. Just as soon as a faint mist appears read the temperature. One method of determining when moisture appears on the surface of the can is to place it on a printed page and observe the reflection of the letters on the polished surface of the can. The letters appear blurred if there is even a slight deposition of moisture on the polished surface.† Avoid breathing on the can. *Why?*

Remove from the water any of the ice which is unmelted. Add slowly a little warm water to the calorimeter until the mist begins to disappear. Read carefully the temperature of the water.

The reading of the thermometer as you cooled the water was a bit too low, since we cannot detect the condensation the instant it appears; and likewise the temperature in the second case, as the water was being warmed, was a trifle too high. By taking the average of these readings we can obtain very nearly the true dew point.

Repeat this experiment several times and take the mean of the average values for the dew point.

Record the temperature of the air in the room, the out-of-door temperature, and the kind of weather.

Tabulate your observations.

Computation. From the humidity tables find the weight of water vapor in one cubic meter of saturated air at the dew

* For a more complete discussion of humidity and its measurement, see Bureau of Standards Circular No. 55, *Measurements for the Household;* U. S. Government Printing Office, Washington, D. C.

† This method was suggested by Prof. F. A. Waterman of Smith College.

point. Also find the weight of water vapor which would saturate one cubic meter of air at room temperature. Finally, determine the per cent of relative humidity.

Optional experiment. Determine the relative humidity by the wet- and dry-bulb thermometers. If this type of hygrometer is not available, one can be improvised from two Fahrenheit thermometers. Wrap some cotton gauze around the bulb of one thermometer and let the lower end of this wick dip into a glass of water. When readings have become stationary, read each thermometer. The wet-bulb thermometer will read lower than the dry-bulb thermometer on account of the evaporation from the bulb surface. Determine the difference in the two thermometers and use the Tables in the Appendix to find the relative humidity.

QUESTIONS

1. Why do you see a cloud of moisture coming from your mouth and nose on a very cold day?

2. Would you expect the relative humidity of a hall crowded with people to remain constant?

3. What methods would you suggest for increasing the humidity in your living rooms?

4. What determines whether the water vapor in the air outside shall be deposited as dew or frost?

5. Why is a relatively high humidity in the summer time so uncomfortable?

EXPERIMENT 36

A COMMERCIAL GAS STOVE

I. *How much does it cost to heat a quart of water from 60° F. to the boiling point 212° F. with a gas stove and kettle?*

II. *What is the combined efficiency of the burner and kettle?*

Small gas stove	Thermometer (Fahrenheit)
Gas meter (a 3-light commercial meter)	Quart measure (copper)
	Hose connections
Saucepan (4 qt.)	Clock or stop watch

Introduction. It is possible with a suitable calorimeter to measure the heat of combustion of illuminating gas when used as a fuel. This is usually expressed in this country in British thermal units per cubic foot of gas used, as, for example, 600 B. t. u. per cubic foot. But the consumer is also interested in the ratio of the heat units which he actually uses, say in boiling water, to the heat of combustion of the gas used. In other words, he wants to know the thermal efficiency of his gas stove and kettle.

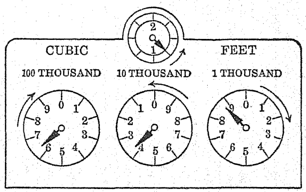


Fig. 70. Gas meter reads 63,800.

Since we do so much of our housework nowadays by electricity, we shall be interested in determining the cost of heating water by a gas stove, and later (Experiment 46) we can compare this with the cost of doing the same thing by electricity.

To measure the gas consumed in our experiment, we shall need to get acquainted with a gas meter. On the ordinary household meter there are three dials (Fig. 70), each with an

index hand. The dial at the left is labeled "100 thousand," which means that for one complete revolution of the hand 100,000 cubic feet of gas have passed through the meter; the next dial is marked 10 thousand, and the right-hand dial 1 thousand. In commercial work these circles are read once a month and the gas bill is made out according to the number of hundred cubic feet. For testing purposes there is a small fourth dial above these three dials and one complete revolution of its index hand records only 2 cubic feet of gas. By using

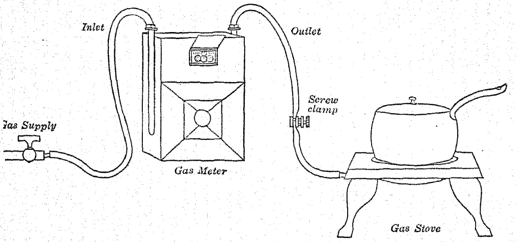


Fig. 71. **How much gas is needed to boil water?**

this little dial we can measure the gas consumed to one tenth of a cubic foot.

Directions.* Connect the gas meter on the inlet side with a gas cock and attach the gas stove to the other side (Fig. 71). Let about a quarter of a cubic foot of gas pass through the meter before lighting the stove. *Why?* Light the gas stove and let it burn until the index hand on the 2-cubic-foot dial has reached some convenient point for reading. Then turn off the gas.

Measure out carefully one quart of water and pour it into a

* This experiment may be performed at home with a gas-range burner and your own gas meter and teakettle.

four-quart saucepan. Get the temperature of the water as near 60° F. as possible. Place the pan of water upon the stove and start heating. Note the initial reading of the gas meter and the time of starting. Allow the heating to continue until the water begins to boil rapidly with steam coming from the bottom. Then turn off the gas and record the time of stopping and the amount of gas consumed.

Record your data and computed results in tabular form.

Computation.

(*a*) *How many cubic feet of gas were consumed in the heating?* (Express the volume to 0.1 cu. ft.)

(*b*) *How many British thermal units were absorbed by the water?* (1 qt. of water weighs 2.08 lbs.)

(*c*) *How many heat units were produced by the gas consumed?* (Assume that 1 cu. ft. of gas gives 600 B. t. u. unless otherwise directed.)

(*d*) *What per cent of the total heat produced by the burning of the gas was used in heating the water?* (This result is the thermal efficiency of the stove and kettle.)

(*e*) *How much does it cost to heat a quart of water from 60° F. to the boiling point 212° F.?* (Unless otherwise directed, assume that the gas costs 10 cents per 100 cubic feet.)

If time permits, repeat this experiment with a cover on the saucepan, and compute the efficiency and cost. *Which is the more economical way of heating water? Why?*

Optional experiments. Determine the cost of heating a quart of water to the boiling point by means of an alcohol stove. Compare the time required for this by an alcohol stove with that required by a gas stove. A blue-flame kerosene stove may be studied in the same way.

Compare the efficiency of different kettles, such as copper, aluminum, and agate ware, for heating water. Consider also the first cost and reasonable length of service of each kind of kettle. Is the shape of the kettle a factor which is important enough to be considered in this work?

QUESTIONS AND PROBLEMS

1. In what respects is the commercial gas stove similar to the laboratory Bunsen burner?

2. In what ways is the gas stove an improvement on the Bunsen burner?

3. How could you determine the cost per hour of operating each of the different burners (including the oven) of your gas stove at home? Try it.

4. Does the heat value of a cubic foot of gas depend upon the elevation of the consumer? Explain how.

5. If the thermal efficiency of a gas heater is 50 per cent, how much will it cost to heat the water for a tub bath? Assume that 6 cubic feet of water must be heated from 50° to 105° F. and that gas costs 10 cents per 100 cubic feet and gives 600 B. t. u. per cubic foot.

MAGNETISM AND ELECTRICITY

EXPERIMENT 37

MAGNETIC LINES OF FORCE

I. *What is the direction of the magnetic lines of force about a bar magnet?*

II. *What is the nature of the magnetic field about certain combinations of magnets?*

Two bar magnets ($15 \times 1 \times 1$ cm.)	Sheet of white paper
Soft-iron washer (2.2 cm. diam.)	Sheet of cardboard
Two strips of wood ($30 \times 1 \times 1$ cm.)	Thumb tacks
Tracing compass, preferably Hahn form (1.0 cm.)	Iron filings in cheese-cloth bag

Introduction. Although we do not know just what magnetism is, yet it is probable that there are in commercial use at the present time at least two hundred million permanent magnets. Besides the straight magnets used in mariners' and surveyors' compasses, we have U-shaped magnets in various electric meters, in every telephone receiver, and in telephone magnetos. Every motorcycle and airplane carries permanent magnets in its magneto, and every Ford automobile has 16 permanent magnets bolted to its fly wheel.

We can learn a great deal about the action of magnets by plotting what Faraday called **magnetic lines of force.** *A line of magnetic force may be defined as a line which indicates at its every point the direction in which a north-seeking pole is urged by the attractions and repulsions of all the poles in the neighborhood.* This assumes that every magnet has its property of attracting iron filings more or less definitely concentrated in two or more spots, called **poles**; and when free to turn, the magnet will set itself with one spot toward the north (the

north-seeking pole) and the other toward the south (the south-seeking pole). Experiments show that

Like poles repel each other,
Unlike poles attract each other ;

also that these forces between magnetic poles vary inversely as the square of the distance between the poles.

Directions. I. *Magnetic lines about a bar magnet.* With the aid of the small tracing compass turn the sheet of paper so that its longer edges are parallel to the compass needle and then fasten the paper to the table with thumb tacks. (In orienting the paper be sure that the permanent magnets are several feet away.) Indicate by an arrow in the corner of the paper the north and south direction. Lay the magnet on the paper near the middle so that its axis lies nearly north and south. Trace with a sharp hard pencil the outline of the magnet and mark the position of its poles with the letters N and S.

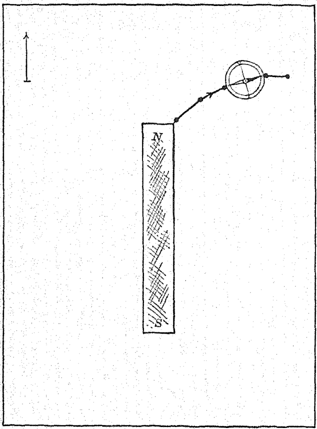


Fig. 72. Plotting magnetic lines of force.

Make a dot near one corner of the north-seeking end of the magnet. Place the tracing compass on the paper beside the

magnet in such a way that the S-pole of the compass needle lies as nearly as possible right over the dot which serves as a starting point. Then mark with a pencil the position of the N-pole of the compass needle (Fig. 72). (If the tracing compass is the Hahn type with four notches in the rim, place the compass so that one notch is directly over the dot and then turn the compass around this point until the needle stands exactly over the line on the compass base.) Move the compass in the direction in which its N-pole points until the S-pole lies exactly over the mark which has just been made. Make a third dot to indicate the position of the N-pole. Continue in this way until you reach the edge of the paper or the south pole of the magnet. Through these several dots draw a line of dashes in the form of a smooth curve and indicate by arrows the direction of the N-pole of the compass needle. Such a line represents a **magnetic line of force.**

Starting at different points about the N-pole of the magnet, trace three or more magnetic lines of force on each side of the magnet. Draw in the same way lines of force which start on the south edge of the paper but do not hit the magnet at all. In this way try to show by as few lines as possible the direction of the force at every point on the paper. Examine with special care the points at which the compass needle seems to be uncertain in its directions. Such points are called **neutral points.** How many are there? How do you account for them? By tracing lines of force on all sides locate the neutral point as accurately as possible and mark its position with a cross.

II. ***Magnetic fields about combinations of magnets.*** Place two bar magnets in line with each other and with the unlike poles about 6 inches apart, as shown in figure 73. Put some strips of wood alongside to support the sheet of cardboard. Sprinkle iron filings evenly over the cardboard and tap lightly so as to shake the filings about a little. They will arrange themselves in regular lines of mag-

Fig. 73. N and S poles.

netic force since each filing gets slightly magnetized by the bar magnets and sets itself in the direction of a tiny compass needle. Draw in your notebook a sketch (reduced in size) of the magnets and the lines of force about and between them.

Remove the iron filings from the cardboard and place a soft-iron washer in the magnetic field between the north and south poles of the two permanent magnets as shown in figure 74.

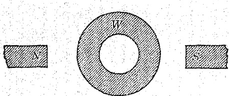


Fig. 74. Iron in a magnetic field.

Replace the sheet of cardboard and again sprinkle the iron filings over it and tap as before. Draw a sketch of this in your notebook indicating by outlines the iron filings and the lines of magnetic force. Explain the difference in the arrangement of the lines of magnetic force caused by the introduction of the soft-iron washer.

Optional experiment. A permanent record of these lines of force can be obtained by using blue-print paper instead of cardboard, and then exposing the paper for a short time in the sunlight. When the iron filings are thrown off and the paper is dipped in water, the picture produced, which is a negative, shows clearly the arrangement of the filings.

Another way of doing this, when a dark room is available, is to use ordinary photographic paper, with the film side up, and expose the paper to the light of an electric lamp held directly over and lighted for a short time. The length of time of exposure must, of course, be determined by experiment. Then the paper is developed in the usual solutions, fixed, and dried, and may be permanently attached to the notebook.

Interesting magnetic fields can be made in this way by using varying combinations of bar magnets and horse-shoe magnets.

QUESTIONS

1. What would you expect the magnetic field to be if you placed two like poles facing each other as in Part II?

2. Could this experiment be done using a sheet of glass instead of cardboard, and then printing on blue-print or photographic paper the position of the iron filings?

3. Is glass a magnetic insulator?

4. Do magnetic lines of force ever cross each other?

5. How far from the end of the magnet do you consider the pole to be located?

EXPERIMENT 38

ELECTROMOTIVE FORCE OF A VOLTAIC CELL

I. *How does the voltage of a cell depend upon the size and nature of the electrodes and on the electrolyte?*

II. *How does the voltage of a group of cells depend upon their arrangement (series and parallel)?*

Voltmeter, triple range (0 – 3, – 15, – 150 volts)
Simple voltaic cell with various electrodes, such as zinc, copper, carbon, and lead
Sulfuric acid (diluted 1 to 20)
Hydrochloric acid dilute
Saturated solution of common salt
Connecting wires
2 Dry cells

Introduction. Electric currents were first produced by chemical action a little more than a hundred years ago by an Italian scientist, named Volta. Today we still use this method for generating small electric currents for intermittent use. The so-called dry cell is the voltaic cell which is extensively used for ringing door bells and for operating telephones, signal devices, flash lights, the ignition circuits of gas engines, and radio sets.

When almost any two conductors are placed in a solution which acts on one of them more than on the other, a difference of potential (*i.e.*, a difference in the electrical condition) is produced between the two conductors. When they are joined by a wire, an electric current flows from one to the other, as shown by certain magnetic effects. When a strip of copper and a strip of zinc are placed in dilute sulfuric acid, we have a simple voltaic cell. It is customary to call the plate which is attacked less by the solution the **positive** (+) **electrode** (the copper) and the other the **negative** (–) **electrode** (the zinc).

We may easily detect which electrode of a cell is positive by connecting it with a voltmeter, which is merely a high-resistance d'Arsonval galvanometer designed to measure voltage, or the difference of potential, directly. The electrode which is connected to the positive (+) terminal of the voltmeter is the positive electrode; that is, provided the needle of the instrument moves across the scale to the right as intended by the manufacturers.

Directions. I. ***Effect of size of cell.*** Connect a simple cell, such as the one shown in figure 75, with the voltmeter. Note the deflection of the needle. Then move the plates as far apart as possible in the jar and again note and record the deflection. Finally lift the plates almost out of the liquids and record the deflection.

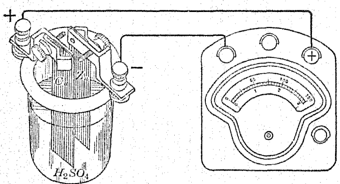


Fig. 75. Voltage of a cell.

What effect does the distance between the plates and the area of the plates immersed seem to have on the electromotive force of a cell?

II. ***Effect of using different metals.*** Note the amount of the deflection caused by the zinc-copper cell. Remove the copper plate and insert a carbon plate or rod and again note the direction and amount of the deflection. If the deflection is in the same direction as above, it shows that the carbon is positive (+) with respect to zinc; but if it is in the opposite direction, then the zinc is positive (+) with respect to the carbon. In this case reverse the connections and measure the voltage. In the same way test the following pairs of metals as electrodes: zinc-lead, lead-copper, and lead-carbon.

Which pair gives the highest voltage?

Which metal among those investigated is positive with respect to some metals and negative with respect to others?

III. ***Effect of different liquids (electrolytes).*** Note again the amount of the deflection when zinc and copper are immersed (*a*) in dilute sulfuric acid (H_2SO_4); (*b*) in dilute hydrochloric acid (HCl); (*c*) in a solution of common salt (NaCl); (*d*) in water (H_2O).

The plates should be thoroughly rinsed off before placing them in a new liquid.

What is the effect of the different liquids used as electrolytes on the voltage of the cell?

IV. ***Effect of series and parallel arrangement.*** Measure the voltage of a dry cell. Connect two dry cells in series, that is, connect the zinc of one to the carbon of the other, as shown in figure 76, and record the deflection. Then connect the same cells in parallel, that is, zinc to zinc and copper to copper, as shown in figure 77, and again read and record the deflection.

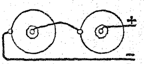


Fig. 76. Cells in series.

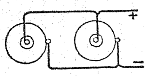


Fig. 77. Cells in parallel.

Compare these results with the deflection of a single cell.

What is the effect of the series arrangement on the voltage?
What is the effect of the parallel arrangement on the voltage?

Optional experiment. In case a direct-reading voltmeter is not available for this experiment, it is possible to substitute a galvanometer with a high-resistance coil (about 1000 ohms) connected in series. When used with such a high-resistance coil, the deflections are almost proportional to the voltage applied.

QUESTIONS

1. Why are carbon and zinc the materials used for electrodes in the dry cell?

2. If the substances used were arranged in a series, such that the first is positive to all the rest, and the next is positive to all except the first, and

so on to the last, which one will be negative to all? (*a*) Which substance comes first? (*b*) Which substance comes last?

3. Is the electromotive series the same with hydrochloric acid as with sulfuric acid?

4. Why is it essential to use a high-resistance voltmeter or galvanometer in this experiment?

EXPERIMENT 39

POLARIZATION AND RECUPERATION OF A DRY CELL

I. *What is the effect of a short-circuit upon the electromotive force and current capacity of a dry cell?*

II. *How rapidly does a dry cell recuperate when left on open circuit?*

Dry cell (Columbia No. 6)	Fuse block with tin-foil fuses
Ammeter (0 – 30 amp.)	Connecting wires and switch
Voltmeter (0 – 3 volts)	Watch or clock

Introduction. While a dry cell is a very convenient source for a small current, it does not operate effectively on continuous or closed-circuit work. When a simple electric cell has its terminals connected by a wire, the current does not remain constant but rapidly becomes weaker. This effect, called **polarization**, is caused by the formation of a gas, usually hydrogen, on the positive plate. This layer of gas increases the internal resistance of the cell and also sets up an opposing electromotive force. In the dry cell manganese dioxide is put in to act as a depolarizer. Nevertheless, there is some polarization, as we shall see in the following experiment.

Directions. I. *Polarization.* Connect a dry cell, as shown in figure 78, using an ammeter with a 30-ampere range for measuring the current, and use a voltmeter with a 3-volt range to measure the voltage. By pressing a button on the voltmeter, a reading may be made directly, and by closing the series switch connected with the ammeter, cell, and fuse, the

current may be measured. Read the ammeter at intervals of 1 minute each until 20 readings have been taken. At the end of this time again read the voltage. Record the observations, that is, the amperes and volts, in tabular form. Plot a curve to show the change in current intensity, letting the time be

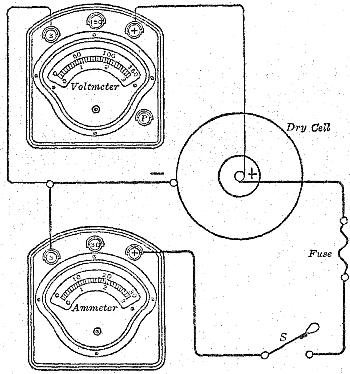


Fig. 78. Testing a dry cell.

represented by horizontal distances and the current (amperes) by vertical distances.

II. ***Recuperation.*** To find how rapidly a cell recovers on open circuit, take readings every minute for 10 minutes, and then for the next 10 minutes, every 2 minutes, and for the next 20 minutes, every 4 minutes. Let the cell remain on open circuit between readings. At the end of this time take one more voltmeter reading and record.

Has the cell entirely recovered its original electromotive force and current capacity in the time allowed?

To show the rate of recovery, plot as before a curve, letting time be represented by horizontal distances, and the current by vertical distances.

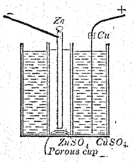


Fig. 79. Daniell cell.

Optional experiment. Construct and test in a similar way a Daniell cell, that is, a two-fluid cell with a porous cup between the sulfuric acid and the copper sulfate solution (Fig. 79). Compare the Daniell cell with the dry cell as to current capacity and the steadiness of the voltage.

QUESTIONS

1. Why is it advisable to use a fuse in series with an ammeter?

2. Why does a dry cell give, when new, approximately 25 amperes on short circuit and only 5 or 10 amperes after it has been in use for some time?

3. Is there a corresponding change in the electromotive force of a dry cell when new and after it has been used?

4. How could you revive temporarily a dry cell which had become weak in current capacity?

5. How do you account for the gradual deterioration of dry cells even when not in use?

EXPERIMENT 40

VOLTAGE BETWEEN POINTS OF A CONDUCTOR

I. *When a steady current is flowing along a conductor, how does the voltage between two points vary with the resistance?*

II. *When the resistance remains fixed, how does the voltage depend upon the current?*

Ammeter (0 – 3 amp.)	Storage battery (3 cells)
Voltmeter (0 – 3 volts)	Variable rheostat
Slide-wire bridge (1 meter)	Switch

Introduction. When a generator is used to furnish electricity to some distant point, it is found that the voltage at the

generator is higher than that at the other end of the line. This "drop in voltage" is due to voltage needed to send the current through the line. In this experiment we shall learn how this drop in voltage depends on the resistance of the line and the current flowing in the line. Incidentally we shall learn how to compute the resistance of the line by measuring the voltage and current and applying Ohm's Law, which states that

$$I \text{ (amperes)} = \frac{E \text{ (volts)}}{R \text{ (ohms)}}.$$

Directions. I. ***Voltage across equal resistances.*** Connect one meter of high-resistance wire in series with a low-reading ammeter (A), an adjustable resistance (R), and a source of

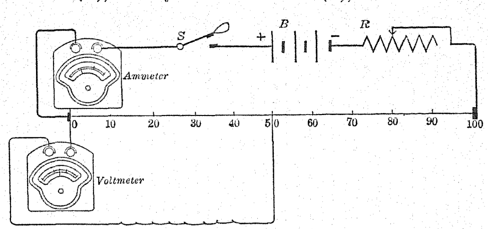


Fig. 80. **What is the voltage between two points?**

steady current, such as a battery of storage cells, as shown in figure 80. Make the connections such that the current enters at the end marked O and adjust the resistance so that the current is one ampere. Touch the + terminal of the voltmeter (V) to the terminal of the wire and touch the other terminal firmly against the wire at a point just 10 centimeters from the O terminal. Read carefully the voltmeter and record this as the **potential difference** or **voltage** between the ends of this 10-centimeter length of wire. In the same way measure the voltage from 10 to 20, 20 to 30, etc., *i.e.* for each 10-centimeter

length along the wire. Assuming that the wire is of uniform cross section, how do the resistances of equal lengths compare? *What conclusion can you draw regarding the voltage across equal resistances carrying the same current?*

II. ***Voltage across varying resistances.*** Connect the + terminal of the voltmeter to the *O* end of the wire and place the other terminal successively at 10, 20, 30 centimeters, etc., and record the voltage for each case. How does the resistance of 20 centimeters of wire compare with the resistance of 10 centimeters? How does the voltage across 20 centimeters of wire compare with that across 10 centimeters? Compare the resistances and voltages for 40-centimeter and 80-centimeter lengths in the same way.

When the current is constant in a conductor, how does the voltage depend on the resistance?

III. ***Effect of varying current on voltage.*** Measure the voltage across 50 centimeters of wire when the current is 0.5 amperes and then 1.0, 1.5, 2.0, 2.5, and 3.0 amperes.

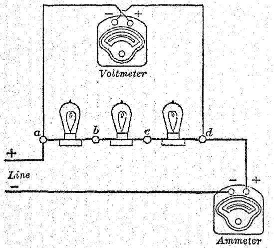


Fig. 81. Voltage-drop in a series circuit.

How does the voltage across any given conductor vary with the current flowing?

Upon what two factors does the voltage across any given conductor depend?

Compute the resistance (ohms) of 10 centimeters of the high-resistance wire used.

Optional experiment. If we allow a current from a 110-volt line to flow through three lamps in series, as shown in figure 81, we may measure the voltage across all three lamps, across two lamps, and across one lamp. If we connect in series with the lamps an ammeter, we may compute the resistance from the voltage and current readings. Find the resistance of each

lamp. Why do the lamps as used in this experiment give no light? Would the resistance of the lamp when the filament is hot be the same as when it is cold? Try it.

Connect the lamps in parallel and measure the voltage and current in the line when all three lamps are in circuit, when two lamps are in circuit, and when only one lamp.

QUESTIONS AND PROBLEMS

1. Why is it desirable in this experiment to use a high-resistance wire with a very small temperature coefficient?

2. What is the function of the variable rheostat in this experiment?

3. Does the ammeter read the same whether the voltmeter is connected across a part of the circuit or not?

4. If the voltage across 5 feet of wire in which 3.5 amperes are flowing is 7 volts, what will be the voltage across 30 feet of the same wire?

5. What will be the voltage across 30 feet of the wire used in problem 4 when the current is 10.5 amperes?

EXPERIMENT 41

RESISTANCES IN SERIES AND PARALLEL

I. *How should an ammeter be used to measure current* (*a*) *in two coils in series,* (*b*) *in two coils in parallel?*

II. *How should a voltmeter be used to measure the voltage* (*a*) *across two coils in series,* (*b*) *across two coils in parallel?*

III. *How can we compute the resistance* (*a*) *of each of the two coils,* (*b*) *of two coils in series,* (*c*) *of two coils in parallel?*

110-volt d-c. line or storage battery	Fuses
2 Resistance coils of manganin wire	Voltmeter (0 – 150)
	Ammeter (0 – 15)

Introduction. The most important electrical measuring instruments are the voltmeter and the ammeter. Each instrument contains a d'Arsonval galvanometer, that is, a fixed permanent magnet and a movable coil. The current which

can be introduced into this coil is very small, but the deflections of the needle, which is attached to the coil, are proportional to the current flowing. In the ammeter there is a shunt, which carries the major portion of the current. In the voltmeter there is a high-resistance series coil, which reduces the current through the movable coil, and the current is proportional to the voltage across the terminals of the instrument.

With reasonable care there is little danger of injuring the voltmeter, provided one uses an instrument of sufficient range. Experience shows that most of the accidents occur in the use of the ammeter, because of the fact that there must always be in the circuit sufficient resistance to regulate the current flowing through the instrument. For example, if a 30-ampere ammeter is connected directly across a 6-volt storage battery, the instrument is burned out almost before it can be connected. This is due to the fact that the battery has almost negligible internal resistance and the resistance of the instrument is also very small. Therefore the rush of current is excessive.

In this experiment we shall learn how to place the ammeter to measure the current, and how to place the voltmeter to measure the voltage, and from these we can calculate the resistance of the coils.

Directions. I. ***Measurement of current. Series.*** Join the two coils in series and connect with the 110-volt d-c. service or other supply of steady current. Place the ammeter (*a*) between coil #1 and the power (Fig. 82), (*b*) between coil #1 and coil #2, (*c*) between coil #2 and the power. Record the average reading of the ammeter in each position. *What do you conclude about the current in a series circuit? Where should the ammeter be placed in a series circuit?*

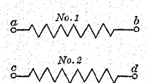


Fig. 82. Two resistors.

Parallel. Join the two coils in parallel and measure the current with the ammeter (*a*) in the line between the coils and the power, (*b*) in the circuit of coil #1 alone, and (*c*) in the

circuit of coil #2 alone. Compare the sum of currents in (*b*) and (*c*) with the current in (*a*). *Where must the ammeter be placed to measure the total current in a branched circuit? Where to measure the current in each branch?*

II. ***Measurement of voltage. Series.*** With the coils in series, measure the voltage across (*a*) the two coils together and (*b*) each coil alone. Compare the sum in (*b*) with the reading in (*a*). *What is the effect upon the current flowing through each part of a series circuit if the resistance of any unit is decreased?*

Parallel. Connect the two coils in parallel and take the voltage between the binding posts of each coil. Compare these readings. Assuming a constant voltage service, *what do you find to be the effect upon the voltage across the group if the resistance of one coil is decreased? upon the current flowing in that coil? upon the current in the other coil? in the line?*

III. ***Computation of resistance.*** From the readings in Parts I and II, compute, using Ohm's Law $\left(R = \frac{E}{I}\right)$, (*a*) the resistance of each coil, (*b*) the combined resistance of the two coils in series, and (*c*) the joint resistance of the two coils in parallel. Compare this latter result with that obtained by computing the joint resistance from the separate resistances $\left(\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}\right)$. In recording the data of this experiment, make careful diagrams to show the connections.

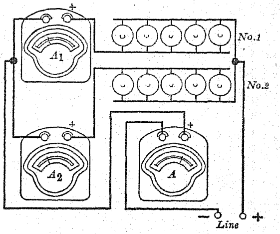


Fig. 83. Currents in lamp circuits.

Optional experiment. A practical form in which to arrange this experiment is that of a lamp board containing 10 lamps connected in two circuits, as shown in figure 83. With this apparatus it is easy to measure

the current in the line and in each branch circuit with various combinations of lamps.

QUESTIONS AND PROBLEMS

1. In determining resistance by the use of an ammeter and voltmeter, why is it essential to read both instruments simultaneously?

2. When the resistance to be measured is high and the current in the circuit is small, the voltmeter is generally connected around *both* the resistance and the ammeter. Why?

3. A lamp of 55 ohms and another of 30 ohms are connected in parallel to a 120-volt line. (*a*) What is the current in each lamp? (*b*) What is the current in the line?

4. If these two lamps were connected in series, (*a*) what would be the current? (*b*) What would be the voltage across each lamp?

EXPERIMENT 42

MEASUREMENT OF RESISTANCE BY WHEATSTONE BRIDGE

How can an unknown resistance be compared with a known resistance by means of a Wheatstone bridge?

Wheatstone bridge (meter-wire form)	D'Arsonval galvanometer
2 Dry cells	Resistance box or known resistance coils
Key	Unknown resistance to be measured

Introduction. The Wheatstone bridge consists essentially of a loop of four resistances, indicated in figure 84 as R, X, m, and n. When the key is closed, the current from the cells flows into the loop at A, and there divides so that part (I_1) goes through AC and part (I_2) through

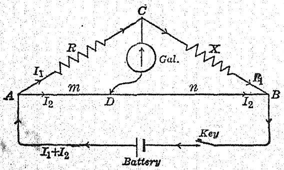


Fig. 84. Diagram of a Wheatstone bridge.

AD. A sensitive galvanometer G is connected between C and D. Then the resistances R, X, m, and n are so adjusted that no current flows through the galvanometer, which means that all of I_1 has to go on through CB and all of I_2 through DB, and also that C and D are "**equipotential**" points. When this adjustment has been made,

the voltage across $AC = I_1R$

and the voltage across $AD = I_2m$.

But since C and D are at the same potential, these voltages are equal, and

$$I_1R = I_2m. \tag{1}$$

For similar reasons $I_1X = I_2n$. (2)

Dividing equation (1) by equation (2), we have

$$\frac{R}{X} = \frac{m}{n}.$$

From this fundamental equation of the Wheatstone bridge, if we know R, m, and n, we can compute X.

In the form of this apparatus shown in figure 85, the resistance ADB consists of a wire one meter long and of uniform cross section. Since the resistances m and n are then directly proportional to the distances AD and DB, the equation becomes

$$\frac{R}{X} = \frac{\textbf{Distance } AD}{\textbf{Distance } DB}$$

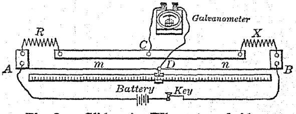


Fig. 85. Slide-wire Wheatstone bridge.

where R is a known resistance such as a resistance box, and the distances **AD** and **DB** are read off on a meter stick. It will be helpful to remember that

$$\frac{\textbf{Left Resistance}}{\textbf{Right Resistance}} = \frac{\textbf{Left Distance}}{\textbf{Right Distance}}.$$

This method of comparing resistances is capable of very great precision and is much used where great accuracy is required. It may be helpful to compare the Wheatstone bridge

to a beam balance, the known resistances corresponding to the set of known weights. When m equals n, we have an equal-arm balance and R equals X.

Directions. Connect the apparatus, as shown in figure 85, using an unknown resistance coil (which will be supplied to you by the instructor) in position marked X. When the key in the battery circuit is closed, the current comes to A where it divides, part going through the known resistance R, along the bar of the bridge (whose resistance is negligible), and through the unknown coil X to B; the other part going by way of the high-resistance wire ADB to B. If the known resistance is made in the form of a resistance box, we may remove the 10-ohm plug, place the slider D connected to the galvanometer in the middle of the meter wire, and make contact for an instant only. If the galvanometer needle moves, it shows that the two points C and D are at different potentials. First try another value for R, say 1 ohm, and if the galvanometer needle swings the other way when contact is made at D, it shows that X, the unknown resistance, lies between 1 and 10 ohms. By trial just as in weighing make a balance between R and X. When it is approximately balanced, make the fine adjustment by sliding D back and forth along the wire until the galvanometer shows no current flowing when the contact is made at D. From the above equation compute the resistance of the given coil.

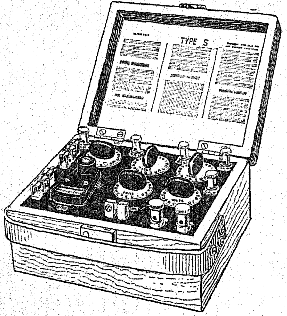


Fig. 86. Portable testing set.

Repeat the experiment twice, using slightly different values for R, the known resistance. Find the average or mean value of these three results.

Optional experiment. In commercial work the Wheatstone bridge is often made in a portable form, such as shown in figure 86. In one box we have the galvanometer, resistance coils, battery, and keys. The known resistances are made with a " dial " control and the ratio coils (which take the place of meter wire) are made on the decimal plan.. If such a portable set is at hand, measure several coils separately, then in series, and finally in parallel. Check up your measurements of the combinations by computations. Find out how such a Testing Set is used to locate a " ground " in a cable. (See Jackson and Black's *Elementary Electricity and Magnetism.*)

QUESTIONS AND PROBLEMS

1. Why is it more accurate in using the slide-wire form of Wheatstone bridge to set the sliding contact D near the middle of the wire?

2. Why is the bridge method not adapted to measuring the hot-resistance of an electric lamp?

3. Why should the galvanometer used with a bridge be very sensitive and dead beat?

4. In the slide-wire form of Wheatstone bridge suppose $R = 10.0$ ohms, $AB = 100.0$ cm., and $m = 37.5$ cm. Compute the value of X.

5. In testing a Wheatstone bridge, 4-ohm and 5-ohm standard coils are inserted in the loop AC and CB. Find the position which D should have on the meter wire ADB.

EXPERIMENT 43

MAGNETIC EFFECT OF A CURRENT

I. *What is the direction of the magnetic lines of force about a wire carrying an electric current?*

II. *What is the direction of the magnetic lines of force about a coil carrying an electric current?*

III. *How is the distribution of magnetic flux passing through a coil changed by inserting a soft-iron core?*

IV. *How should the windings of an electromagnet be connected?*

Dry cell	Compass (2.5 cm. needle)
Reversing switch (or commutator)	Soft-iron rod or core
Connecting wires	U-shaped iron core

Introduction. One of the difficulties about electric currents and one of their fascinating characteristics is that they are invisible. We study electricity largely through its effects, and of all these effects the magnetic effect is doubtless the most useful. As long ago as 1819 a Danish physicist, named Oersted, discovered that an electric current flowing along a wire near a compass deflected the needle from its usual north and south position. This lead to a study of the magnetic field around a straight wire carrying a current, around a loop or coil of wire, and finally around a coil of wire with an iron core. This iron core surrounded by a coil of insulated wire, called an **electromagnet**, is an essential part of the electric bell, telegraph, and telephone, as well as of the electric generator and motor.

In this experiment we shall study the magnetic field about a wire and about a coil carrying a current, and then we shall study the practical application of these principles in the electromagnet. We shall assume that the N-pole of the magnetic needle points in the direction of the magnetic lines of force and that the direction in which the electricity flows through a dry cell is from zinc to carbon inside the liquid and *from carbon to zinc in the external circuit.*

Directions. I. ***Magnetic field about a wire carrying current.*** (*a*) Connect a dry cell to a reversing switch and then lead the current from south to north over a compass, as shown in figure 87. Close the circuit by means of the switch and record the deflection.

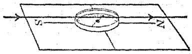


Fig. 87. Current flowing over a compass.

(*b*) Turn the switch so as to reverse the current, causing it to flow from north to south over the compass. Record the deflection.

Compare these results with what might be expected from the so-called **thumb rule**:

If one grasps the wire with the right hand so that the thumb points in the direction of the current, the fingers will point in the direction of the magnetic field.

(*c*) Put the wire under the compass and without changing the direction of the current note the direction of the deflection.

(*d*) Pass the current from the cell over the compass from south to north, holding the wire close to the face of the compass, and make the return wire pass under the compass so that a loop is made around the compass. Is the deflection greater or less than in (*a*)? Why?

II. ***Magnetic field about a coil carrying current.*** (*a*) Loop the wire used in I (*d*) several times around the compass in such a way that the plane of the coil is north and south. What change in the deflection is produced by increasing the number of turns in the coil?

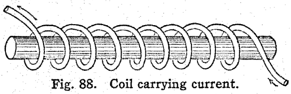


Fig. 88. Coil carrying current.

(*b*) Make a helix (Fig. 88) by wrapping the wire say fifty times around a lead pencil. Connect this to the switch or commutator as in I, and see whether or not such a helix carrying a current acts as a magnet with one end attracting the north pole of the compass and the other repelling it. Reverse the current through the helix by means

of the commutator and record the effect that is produced upon the poles.

Compare these results with what might be expected from the **thumb rule for a coil**:

Grasp the coil with the right hand so that the fingers point in the direction of the current in the coil, and the thumb will point to the north pole of the coil.

III. ***Electromagnet.*** (*a*) Make an electromagnet by putting a large iron nail or bolt inside the helix. *Does this iron core make the poles stronger or weaker than before? How do you know?*

(*b*) Wind the two sides of the U-shaped piece of iron with a wire carrying a current in such a way that one end which has already been marked will be an N-pole and the other an S-pole. *Test the polarity of this horseshoe with a compass.*

In recording the results of these experiments make very simple but clear diagrams, showing the polarity and the direction of the current in each case.

Optional experiment. A lifting magnet is of great commercial importance in handling scrap iron and small steel castings. This

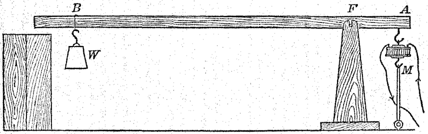


Fig. 89. How much does an electromagnet pull?

electromagnet has great lifting force because the air gap is small and the iron circuit for the magnetic flux is short. We may study the lifting force of a model magnetic hoist by means of a long lever arranged as shown in figure 89. Connect the magnet to a storage battery or to the lighting circuit (if it is direct-current) with a suitable rheostat (such as a bank of lamps) and ammeter in series. Slide the movable weight along the bar away from the fulcrum and record the

position of this weight when the magnet is separated from its armature. Also record the current intensity at the exact time of separation. Repeat the experiment, using different current strengths in the magnet. Then plot a curve to show the relation between the current passing through the coil of the electromagnet and its lifting force.

QUESTIONS

1. How could you determine whether a current were flowing along a wire? How could you determine its direction?

2. Given two electromagnets which are to be tested for lifting strength. How could you do this with a box of iron brads?

3. What advantages has the horseshoe electromagnet over the straight electromagnet?

4. What advantages has the electromagnet over the permanent magnet?

5. What sort of iron is best suited for the cores of electromagnets?

6. What are the materials used to insulate the wire of a commercial electromagnet? What advantages has each?

7. What difference does it make in the operation of an electric bell if the current is reversed?

8. Would you expect to find any magnetism in the iron core of an electromagnet after the current is cut off? Try it.

EXPERIMENT 44

MEASUREMENT OF CURRENT BY A COPPER COULOMBMETER

How may an ammeter be calibrated by the weight of copper deposited in a certain time?

Copper coulombmeter
Copper sulphate ($CuSO_4$) solution with a little sulfuric acid and alcohol
Ammeter (0 — 3)
Adjustable resistance
Watch or clock with second hand
Beam balance and weights
Storage battery or supply of steady current

Introduction. By international agreement the practical unit of quantity of electricity is the **coulomb**. This unit is defined

as that quantity of electricity which deposits 0.001118 grams of silver. It has also been agreed that the unit rate at which electricity flows along a conductor shall be the **ampere**, or one coulomb per second. Usually we are more interested in the rate of flow (amperes) than in the quantity of electricity (coulombs). Therefore we frequently use ammeters (or ampere meters) but only occasionally coulombmeters. We may use the latter to calibrate an ammeter.

The coulombmeter depends on the chemical effect of an electric current. When an electric current passes through a water solution of a salt, base, or acid, the latter is decomposed. The products of decomposition usually appear at the electrodes, which lead the current into and out of the solution. If the solution is an acid, such as sulfuric acid, hydrogen gas appears at the **cathode** (the terminal by which the current leaves the solution); and if the solution contains a metallic salt, such as silver nitrate or copper sulfate, the metal is often deposited on the cathode. Now the quantity of metal deposited or of gas generated depends directly upon the quantity of electricity passing through the solution. The weight of copper deposited under certain specific conditions has been very carefully determined and found to be 1.186 grams per ampere-hour.

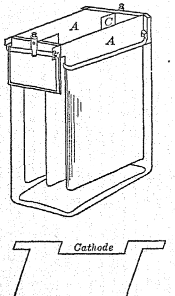


Fig. 90. Coulombmeter.

The object of this experiment is to calibrate an ammeter, that is, find the error in an ammeter by means of a copper coulombmeter.

Directions. The copper coulombmeter consists of a glass jar with two copper anode plates *A*, *A* and one cathode, or gain, plate *C* placed between them (Fig. 90). About 50 square centimeters of cathode surface is allowed for each ampere of current, and the liquid is a

solution of copper sulfate ($CuSO_4$) slightly acidulated with sulfuric acid (H_2SO_4) and containing a little alcohol.* The gain plate (cathode) is first made perfectly clean by rubbing with fine emery until bright and then wiping with a clean dry cloth. After it is cleaned the part which is to be immersed must not be touched by the fingers.

Weigh this clean cathode as accurately as you can and set it aside.

Connect the ammeter which is to be calibrated with an adjustable resistance in circuit with the coulombmeter and some supply of steady current, such as a storage battery. Insert in

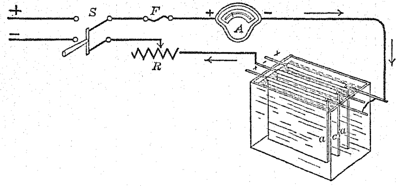


Fig. 91. Testing an ammeter.

the coulombmeter a trial cathode plate, not the clean one, but of the same size as the one to be used. The current must be made to enter at the outside plates (anodes) and emerge at the middle, or gain, plate (cathode) (Fig. 91). Close the circuit and adjust the resistance to give the desired current (from 1 to 2 amperes).

Open the circuit and replace the trial cathode by the clean weighed cathode and again close the circuit, noting exactly the time (hr. min. sec.). Record the ammeter reading every ten minutes and keep the current constant. After 30 or 40 minutes, break the circuit and at once remove the gain plate. Note the

*Add 200 g. crystallized copper sulfate to 1000 cm^3. water and when it is all in solution, filter and add 50 g. sulfuric acid and 50 g. alcohol (ethyl).

deposit of copper. Rinse off in clean water and then in alcohol and dry quickly. Reweigh and determine the gain as precisely as possible.

Compute the gain in weight per hour.

Assuming that 1.186 grams of copper are deposited by one ampere in one hour, *compute the average current.*

Compare this value of the current with the average reading of the ammeter.

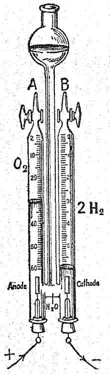


Fig. 92. Water decomposed.

Optional experiment. A much quicker method of calibrating an ammeter is to use a **gas coulombmeter.** For this purpose the Hoffman apparatus for the electrolysis of water (Fig. 92) may be used.* To get reliable results, use a 10 per cent solution of chemically pure sulfuric acid made with distilled water. With a stop watch note the length of time required to collect 40 cubic centimeters of hydrogen with a current of about 0.25 amperes. Reduce the observed volume of hydrogen collected to standard conditions (76 cm. of mercury and 0° C.). Assuming that a liter of hydrogen under standard conditions weighs 0.090 grams, calculate the weight of hydrogen. The electrochemical equivalent of hydrogen is 0.0376 grams per ampere-hour; calculate the current in amperes and compare the result with the average reading of the ammeter.

Make several trials.

QUESTIONS AND PROBLEMS

1. What advantage is there in using two anode copper plates instead of one?

2. What industrial applications are made of the electrolysis of copper sulfate?

3. Why is it essential in this experiment that the current be kept constant?

* In another form of apparatus, both hydrogen and oxygen gases are collected in the same tube and a solution of sodium hydroxide (8%) and nickel electrodes are used.

4. The copper used for electrical machinery is refined by electricity. How long will it take 250 amperes to refine a ton of copper? (1 lb. = 454 g.)

5. Hydrogen for commercial purposes is usually prepared by the electrolysis of water. How many amperes will be required to generate 1 million cubic feet of hydrogen (under standard conditions) in 24 hours? Assume that the density of hydrogen is 0.0053 pounds per cubic foot.

EXPERIMENT 45

CHARGE AND DISCHARGE OF A STORAGE BATTERY

How do the voltage and the density of the electrolyte change during the process of charge and discharge?

Storage battery (3 cells)	Rectifier, such as "Tungar," for a-c. circuit
Voltmeter (0 – 15)	Bank of lamps, to control discharging current or charging current on d-c. circuit
Ammeter (0 – 30)	
Hydrometer, syringe form	

Introduction. The extensive use of the storage battery on automobiles for starting, lighting, and ignition purposes has made some knowledge of its proper use an everyday necessity. What you see on the outside is a black box with lead strips at the top. In this box are three or six cells, according as it is a 6-volt or a 12-volt battery. Each cell is contained in a jar of hard rubber or of some other insulating material. The positive plates, which are brown in color, are coated with lead dioxide (PbO_2), and the negative plates, which are gray, are made of spongy lead (Pb). These plates are sandwiched together with one more negative plate than positive. In these portable batteries the plates are made very thin and are set very close together with insulating separators (usually of wood) in between. The electrolyte consists of sulfuric acid and distilled water (about 1 part acid to 3 parts water by volume).

To charge a storage battery wires are connected with the lead terminals and a direct current of electricity is passed through it for several hours. During this process oxygen is generated at

the positive plates, forming lead dioxide, and hydrogen at the negative plates. The electricity is not stored in the battery but produces a chemical change which is best represented as follows:

$$\begin{array}{ccccccccc} & & & \text{Discharge} \longrightarrow & & & & & \\ \text{Positive} & & \text{Electrolyte} & & \text{Negative} & & & & \\ PbO_2 & + & 2\,H_2SO_4 & + & Pb & = & 2\,PbSO_4 & + & 2\,H_2O \\ \textit{Lead dioxide} & & \textit{Sulfuric acid} & & \textit{Lead} & & \textit{Lead sulfate} & & \textit{Water} \\ & & & \longleftarrow \text{Charge.} & & & & & \end{array}$$

When the storage battery is being used, that is, when it discharges, the chemical action takes place in the reverse direction and the lead dioxide is slowly used up. Incidentally the solution becomes more dilute with the formation of water, as shown in the chemical equation. Thus we see that we can learn very much about the condition of a storage battery by determining the density of its electrolyte.

Directions. ***Charging.*** Connect the storage battery to some source of direct current, such as a Tungar rectifier or a d-c. 110-volt line, with a lamp bank to control the current. Be sure to connect the positive terminal (marked + or red) of the battery to the positive wire of the line. Insert an ammeter in series with the battery and adjust the charging current to about 3 amperes. Connect a voltmeter so as to read the voltage across the terminals of the battery. At regular intervals of 5 minutes each, record the voltage, current, and time. With each set of readings the charging circuit should be open long enough to read the voltage of the battery. Also measure the density of the electrolyte by means of a hydrometer. Continue the process of charging until the density of the acid solution becomes constant.

Discharging. Allow the battery to discharge through a bank of lamps or a rheostat which takes about 3 amperes. Again read the ammeter, voltmeter, and hydrometer at regular intervals of 5 minutes each until the density of the electrolyte becomes 1.150.

Results. The results of this experiment may best be presented in a series of curves, showing the change of *voltage* (vertically) and change in *density* of the electrolyte (vertically) with *time* on charge (horizontally). In the same way curves may be plotted to show these changes with discharge.

Assuming that we discharge the battery to the same condition as when we started charging, we may compute its efficiency; that is, the ratio of the watt-hours got out to the watt-hours put in. Thus,

$$\text{Efficiency} = \frac{\text{watt-hours output}}{\text{watt-hours input to recharge}}$$
$$= \frac{\text{amp.-hours output} \times \text{av. discharge voltage}}{\text{amp.-hours input} \times \text{av. charging voltage}}.$$

Optional experiment. If an Edison storage battery is available, charge and discharge it. In this case, however, the condition of the battery cannot be determined by means of a hydrometer. Why not? How can you test its condition? Compute its efficiency.

QUESTIONS AND PROBLEMS

1. Why must the ammeter connections be reversed when the battery is discharging?

2. What does the *gassing* of a storage battery indicate?

3. Why is it necessary to add distilled water to a storage battery occasionally?

4. What is the electromotive force of a lead cell which has an internal resistance of 0.002 ohms and has a terminal voltage of 1.98 volts when discharging at the rate of 30 amperes?

5. What is the internal resistance of a lead cell which has an e. m. f. of 2.00 volts and a terminal voltage of 1.90 volts when discharging 25 amperes?

EXPERIMENT 46

AN ELECTRIC HEATER

I. *How much does it cost to heat a quart of water from 60° F. to the boiling point, 212° F., with an electric stove and kettle?*
II. *What is the combined efficiency of an electric stove and kettle?*

Small electric stove (hot plate)	Thermometer (Fahrenheit)
Voltmeter (0 – 150)	Quart measure (copper)
Ammeter (0 – 15)	Connecting wires
Saucepan (4-qt.)	Clock or stop watch

Introduction. Electric heating appliances have proved to be very convenient but more expensive to operate than gas. In spite of this handicap electric flatirons, toasters, percolators, chafing dishes, and radiators are now common in the household, and electric soldering irons, glue cookers, melting pots, automobile-tire vulcanizers, and electric ovens are much used industrially. The principle is the same in all these devices. The electrical energy is transformed into heat by resistance, just as mechanical energy may be transformed into heat by friction. The heating element of the electric stove consists of a high-resistance ribbon or wire which is supported on or embedded in some insulating material.

The user of such an appliance is interested in two things, *first,* the cost of operation, and *second,* its efficiency, that is, how much of the electrical energy put into the device is got out as useful heat.

We have already in Experiment 36 determined the cost of operation and efficiency of a gas stove and kettle. Now by performing a similar experiment with an electric stove and the same kettle we shall be able to compare these two methods of heating.

Directions. To measure the *input* of electric energy, we have simply to connect an ammeter in series with the electric stove (hot plate) and a voltmeter across the line, as shown in

figure 93. Use the same pan or kettle as in Experiment 36 and pour a quart of water which is as near to 60° F. as possible into the pan. Before turning on the current let the instructor inspect your connections; when everything is in order, start heating and note the exact time, recording the hour, minute, and second.

Record the voltmeter and the ammeter at regular intervals of 2 minutes each until the water boils. Then turn off the current and note the exact time of stopping.

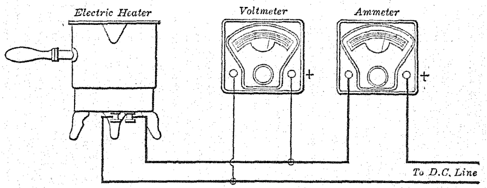


Fig. 93. How much electric power does the heater take?

Computations. Find the average reading of the voltmeter and of the ammeter. From these mean values of the voltage and current and the time required to boil the water, compute the number of kilowatt-hours of electricity used. Assuming that electricity costs 10 cents per kilowatt-hour (unless otherwise directed by the instructor), compute the cost of heating 1 quart of water to the boiling point.

Compare this cost with the cost of doing the same work by gas (Exp. 36).

To determine the efficiency of the electric heater and kettle, we must find the ratio of the heat units absorbed by the water (output) and the heat developed by the current (input). We may easily compute the heat units absorbed by the water as follows: British thermal units* (B. t. u.) = weight of water

* The efficiency can be equally well computed in the metric system. Output in calories = weight of water (g) × rise in temperature (° C.). Input in calories = 0.24 × watts × seconds.

(lbs.) × rise in temperature (F.); and the heat developed by the current in B. t. u. $= \dfrac{\text{watts} \times \text{seconds}}{1054}$. Therefore the

$$\text{efficiency} = \frac{\text{weight of water (lbs.)} \times \text{rise in temp. (F.)}}{0.00095 \times \text{watts} \times \text{seconds}}.$$

Compute the efficiency of the stove and kettle. Compare this value with that obtained for the gas stove.

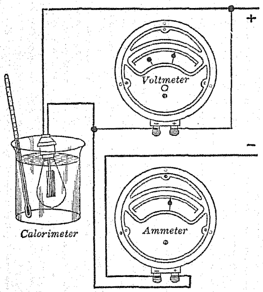


Fig. 94. **Heat given by 1 watt.**

Optional experiment. We may determine experimentally the number of joules (watt-seconds) of electricity which are equivalent to one unit of heat by passing an electric current through a coil or lamp entirely submerged in water in a calorimeter (Fig. 94). By means of a voltmeter, an ammeter, and a watch we can measure the electrical energy; and by means of scales, weights, and a thermometer we can measure the heat units.

QUESTIONS AND PROBLEMS

1. Why is the efficiency of the electric stove less than 100 per cent?

2. Would you expect the immersion type of electric heater to be more efficient? Why?

3. What advantages have electrical heating appliances over gas apparatus used for the same purpose?

4. Assuming that one joule (watt-second) is equivalent to 0.24 calories, compute the number of calories which could be obtained for 1 dollar. Electricity may be assumed to cost 10 cents per kilowatt-hour and the heater has 100-per-cent efficiency.

5. Assuming that 1 B. t. u. is equivalent to 1054 joules, compute the number of B. t. u.'s which are equivalent to 1 kilowatt-hour.

EXPERIMENT 47

INDUCED CURRENTS

I. *How may currents be induced by means of a magnet?*
II. *How may currents be induced by means of an electromagnet?*
III. *How may a coil be moved in a magnetic field to generate a current?*

D'Arsonval galvanometer	Bar magnet
2 Dry cells	Soft-iron core
2 Coils of about 800 turns of No. 28 copper wire	Reversing switch
	U-shaped steel magnet

Introduction. The dry cell produces an electric current by means of the chemical action of the sal ammoniac paste on the zinc can. Here the zinc acts as the fuel and a very expensive fuel it is. But the quantity of electricity which can be produced in this way is entirely inadequate for our modern power purposes. Fortunately another method of producing electricity, or rather of converting mechanical energy into electricity, has been discovered and now finds its applications in electric generators of enormous capacity in our power stations.

In this experiment we shall study the fundamental principles of induced currents produced by a permanent magnet, by an electromagnet, and by a coil moving in a magnetic field.

Directions. I. ***Induction by a magnet.*** To see which way the needle of the d'Arsonval galvanometer moves when the current enters at the right-hand binding post, we may short-circuit the instrument with a stout copper wire and connect with a dry cell so that the current enters at the right-hand terminal of the galvanometer. Place a piece of paper near the instrument and record the direction of the deflection with an arrow when the right terminal is made positive (+). Connect to the galvanometer (now without any shunt) a coil of many turns (about 800 turns of No. 28 copper wire).

(*a*) Now move the coil downward quickly over the N-pole of the bar magnet and record the direction and amount of the deflection. From this deflection determine the direction of the current induced in the coil. While this current was flowing in the coil, it made the coil a temporary magnet. *What was the polarity of the side of the coil approaching the N-pole of the magnet?*

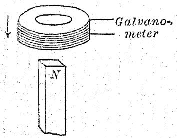


Fig. 95. Current induced in coil.

NOTE. In recording the results of these experiments it will be helpful to use simple diagrams (Fig. 95) with arrows and labels to show the direction of the motion, the current, and the poles.

(*b*) Quickly remove the coil from the magnet and record the direction and amount of the deflection. Compare the direction and amount of the current thus induced with that in part (*a*). *What is the polarity of the end of the coil that last leaves the magnet's N-pole?*

(*c*) Repeat (*a*) and (*b*) using the S-pole of the magnet, and in each case determine the direction of the current induced in the coil. *Is the direction of the induced current such as to oppose or to assist the motion of the coil?*

II. ***Induction by an electromagnet.*** Insert an iron rod in a coil S which is connected to the galvanometer. Connect through a commutator one or two dry cells to a similar coil P which is placed on the iron rod beside coil S (Fig. 96).

(*a*) Now close the circuit by the commutator or switch and record the deflection of the galvanometer. From this determine the direction of the current induced in the coil S. *Was this current induced in coil S* (called the **secondary**) *in the same direction as the current in coil P* (called the **primary**)? *Explain how this might be expected from the experiment in Part I.*

(*b*) Break the circuit at the commutator and note direction and amount of the deflection. Compare this with that induced when the circuit is closed.

Is the induced current in the same direction as that which is flowing in the primary coil, or in the opposite direction? Note that the current is induced by the *changes* in the magnetism of

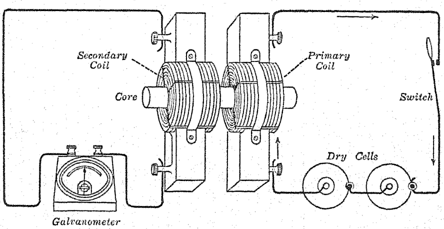


Fig. 96. A current induced in the secondary coil.

the electromagnet. *Is the direction of the induced current such as to oppose or assist the changes in the magnetism of the iron core?*

III. ***A current generated by moving a coil in a magnetic field.*** Hold the coil S, which is connected to the galvanometer, between the poles of a U-magnet in such a way that the plane of the coil is at right angles to the line joining the poles (Fig. 97). Quickly turn the coil a quarter turn so that the plane of the coil is parallel to the magnetic field. Observe the direction of the induced current. After the galvanometer has come back to zero, rotate the coil another quarter turn and note the direction of the induced current. In a similar manner continue to rotate the coil one quarter turn at a time. *In what position is the coil when the induced current is reversed?*

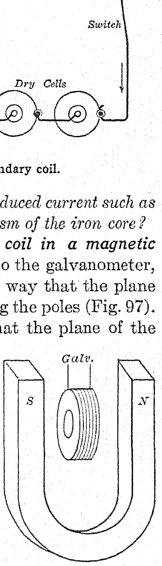


Fig. 97. Effect of turning the coil.

Optional experiment. Study the ignition system of an automobile. What is the source of current? How is the voltage raised? What

is the purpose of the vibrator? What is the function of the condenser? What is the most vital part of the spark plug? What takes the place of a distributor in a Ford car? Make a careful diagram of the different parts of the ignition system of some automobile and explain its advantages and disadvantages.

QUESTIONS

1. Show how the Principle of Conservation of Energy applies to these experiments on induced currents.

2. Why is the induced current produced by using an electromagnet so much greater than that produced by a permanent magnet?

3. Why is the current induced in the secondary stronger when the primary circuit is broken than when it is closed?

4. Show how the principle illustrated in Part III is utilized in the d'Arsonval galvanometer.

5. How is the d'Arsonval galvanometer modified in the (*a*) commercial ammeter? (*b*) voltmeter?

EXPERIMENT 48

ELECTRIC GENERATOR AND MOTOR

I. *What are the fundamental principles upon which the electric generator operates?*

II. *What are the fundamental principles which control the operation of an electric motor?*

Model motor (St. Louis form)	Galvanometer
Electromagnet field for motor	Small variable rheostat (10 ohms)
A-c. armature for same	Compass
2 Dry cells	Push button or switch

Introduction. The development of the electric generator has revolutionized modern industry by furnishing cheap electricity. It has enabled us to transform the enormous energy of the steam engine and water wheel into electricity. After the discovery of induced currents by Faraday and Henry it took about 40 years to develop the practical generator.

Today we use the electric motor for so many purposes in the home, on the streets, and in the shop, that we are liable to forget that it is the result of a vast amount of experimental study. Nevertheless we shall learn that the essential parts of a generator or motor are few and their operation is simple to understand.

First let us remember that a **generator** is a *reversible* machine and when it is supplied with electricity and we use it to drive some machine, like a street car or sewing machine, we call it a **motor**. The most important parts of this machine, sometimes called a dynamo, are (1) the *field*, which furnishes the magnetic flux; (2) the *armature*, usually the rotating element and the one in which a current is generated or which, if supplied with current, produces rotation; (3) the *commutator* (in a-c. machines the slip rings), at which the current is collected or through which the current is sent into the armature; (4) the *brushes*, which slide on the commutator (or rings) and provide a method of taking off the current or putting it into the armature.

Directions. I. *Magneto.* Put the armature with the slip rings in position and bring the permanent magnets up close to the armature (Fig. 98). Adjust the brushes so that they rest on the slip rings and then connect the brushes to the galvanometer.

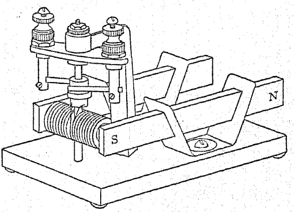


Fig. 98. Model form of magneto.

(*a*) Slowly rotate the armature and note carefully the deflections of the galvanometer. *Is the induced current alternating or uni-directional? If alternating, in what position is the armature when the current reverses its direction?*

(*b*) Rotate the armature at different speeds. *What is the effect on the induced current of increasing the speed?*

II. ***Direct-current generator.*** Replace the slip-ring armature with the armature having a commutator and carefully adjust the brushes. Set the permanent magnets close up to the armature.

(*a*) Rotate the armature in one direction and note the direction of the deflection. Rotate in the opposite direction and note the direction of the deflection. *Explain.*

(*b*) Rotate the armature at different speeds. *How does increasing the speed affect the induced current?*

(*c*) Move the magnets away from the armature and *note the effect on the induced current. What two factors have you found that affect the induced current and therefore the electromotive force produced by a generator?*

III. ***Direct-current motor.*** Remove the galvanometer and connect two dry cells in series with the armature and a push button or switch. Set the brushes so that the polarity of the armature core changes at the proper place to produce continuous rotation. Test with a small compass the polarity of the core for a complete revolution of the armature.

(*a*) Find what effect is produced on the speed of the motor by the gradual weakening of the field when the magnets are moved away from the armature.

(*b*) Find the effect on the speed of the motor of reducing the armature current. This may be done by introducing resistance or using one dry cell instead of two.

(*c*) *How would you reverse the direction of rotation of a motor?* Try the effect of reversing the armature current. Try the effect of reversing the magnetic field by turning each magnet end for end. Try the effect of reversing *both* the armature current and the field.

IV. ***Series- and shunt-wound motor.*** Remove the permanent magnets and connect an electromagnet in series with the armature and the dry cells, as shown in figure 99. Reverse the current and *explain the effect.*

Connect the electromagnet in parallel with the armature.

Reverse the current from the battery. *Explain the effect, if any, on the direction of rotation.*

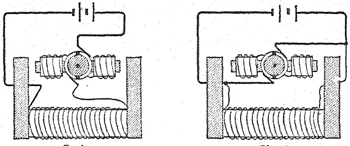


Fig. 99. Series and shunt motors.

Optional experiment. If a small shunt-wound generator (about 0.25 H. P.) with a motor to drive it is available, a very profitable experiment may be carried out with a voltmeter, an ammeter, 2 rheostats, and a speed counter. What effect has speed on the voltage of the generator? What effect upon the voltage does resistance introduced in the field circuit have? Why does the voltage not drop to zero when the field current becomes zero? What effect upon the voltage does an increase in the load (line current) have?

QUESTIONS

1. What is the function of each of the four essential parts of a dynamo — (*a*) magnet, (*b*) armature, (*c*) commutator, and (*d*) brushes?

2. The speed of a motor can be changed somewhat by rotating the brush holder and thus shifting the point of commutation. How does this affect the speed? Why? Try it.

3. Name a dozen practical applications of the electric motor. Indicate which are series-wound and which are shunt-wound.

4. Why is it the commercial practice to use very large electric generators in modern power stations?

5. What are the advantages of using many small motors in shops and factories?

EXPERIMENT 49

EFFICIENCY OF AN ELECTRIC MOTOR*

What is the ratio of the mechanical output of an electric motor to the electrical input?

Shunt motor (0.25 horse power)
110-volt direct-current line or storage battery
Ammeter (0 – 30)
Voltmeter (0 – 150)
Two spring balances (20 lbs.) and support
Cord or strap for brake
Speed counter
Watch

Introduction. An electric motor receives electrical energy and delivers mechanical energy. To compute its efficiency, that is, the ratio of the output to the input, we shall need to

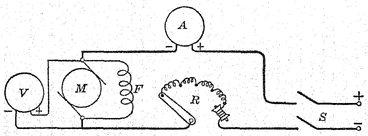


Fig. 100. Connections for testing a shunt motor.

express both output and input in some common unit. We can easily calculate the **input** in watts, which is equal to the product of volts times amperes. By inserting an ammeter *in* the line and putting a voltmeter *across* the terminals of the motor (Fig. 100), we can measure the intensity of the current I and the electromotive force E. Then

$$P \text{ (watts)} = E \text{ (volts)} \times I \text{ (amperes)}.$$

To get the mechanical **output** we may make a **brake test.** A very simple form of brake consists of a belt or cord passing under a pulley on the motor shaft and attached to two spring

*Three or four students may well work together on this experiment.

balances, as shown in figure 101. If the motor rotates clockwise, as indicated, it is evident that the spring balance A will have to exert more force than balance B because of the friction of the pulley on the cord. The amount of this friction is equal to the difference between the readings of A and B, and it is exerted each minute through a distance equal to the circumference of the pulley times the revolutions per minute. The *work done in one minute* is equal to the *friction times the distance per minute.*

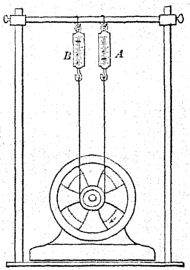


Fig. 101. Brake test of a motor.

We may express this output in watts by remembering that 1 horse power = 33,000 foot-pounds per minute = 746 watts. Therefore

$$\textbf{output (watts)} = \frac{\text{circum. (ft.)} \times \text{r.p.m.} \times \text{friction (lbs.)}}{33{,}000} \times 746.$$

$$\text{Then the } \textbf{efficiency} = \frac{\text{output}}{\text{input}}.$$

Directions. First determine the circumference of the pulley by measuring the length of fine wire or thread required to make one turn around the pulley. To determine the number of revolutions per minute (r. p. m.), hold a speed counter (Fig. 102) against the end of the motor shaft for half a minute and then double the number recorded.

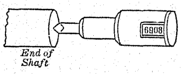


Fig. 102. Counting revolutions.

Connect a small shunt-wound motor M to some supply of direct current. Insert the ammeter A *in* the line and the voltmeter V across the terminals of the motor, as shown in figure 100. It is well to use a double-pole switch S with a suitable resistance R at one end to control the rush of current when starting the motor.

Before closing the switch to start the motor, let the instructor inspect and approve your arrangement of the apparatus. In starting the motor first turn the rheostat arm so as to throw in the resistance; as the motor speeds up, gradually cut out the starting resistance. *Why?*

Put on the load by increasing the tension on the brake band so as to slow down the motor a little. Keeping this pull steady, get the speed of the motor and at the same time read the spring balances, the ammeter, and the voltmeter.

Repeat the experiment, putting more load on the motor by pulling more strongly on the balances. Finally, make a third trial with still more load on the motor. It would be interesting to make these tests at half load, at full load, and at 50 per cent overload as rated on the name plate.

Record the data and results in some convenient tabular form.

Results. Compute in each trial the electrical power put in expressed in watts; also the mechanical power got out expressed in watts; and then the efficiency expressed as per cent.

Why does the intensity of the current supplied to the motor change as the brake load increases?

Why cannot a motor have an efficiency of 100 per cent?

Does the efficiency of the motor change under different loads?

Optional experiment. Sometimes it is inconvenient to apply the brake test to an electric motor. In such a case we can compute its efficiency by the method of losses. That is,

$$\text{Efficiency} = \frac{\text{output}}{\text{input}} = \frac{\text{input} - \text{losses}}{\text{input}}.$$

The various losses in a motor are the I^2R losses in the field and armature windings, core (iron) losses in the armature core and pole faces, bearing friction, and wind friction.

Measure the input of a shunt motor without load. This gives approximately the sum of the I^2R loss in the shunt field, core loss, bearing friction, and wind friction. Then measure the input again but with the motor under full load. Finally measure the resistance of the armature when stationary. Compute the I^2R loss for the armature when the motor is carrying full load. Add this to the watts

obtained in the first measurement and get approximately the total losses of the motor under full load. From this compute the output and efficiency.

QUESTIONS AND PROBLEMS

1. What is meant by the " back electromotive force " of a motor?

2. Why is the starting current of a shunt motor so much larger than the running current?

3. What precautions should be taken in starting a shunt motor?

4. At 10 cents per kilowatt-hour, how much will it cost per week of 54 hours to run a motor which has an average load of 10 horse power and an average efficiency of 85 per cent?

5. On the name plate of a shunt motor are given the following data: 3000 r. p. m., 115 volts, 38.5 amperes, and 5 h. p. Compute its efficiency.

EXPERIMENT 50

ALTERNATING-CURRENT TRANSFORMER *

I. *How is electrical energy transferred from the primary to the secondary coils of a transformer?*

II. *What relation exists between voltages across primary and secondary coils and the number of turns?*

Simplified transformer set (Burns' form)
A-c. voltmeter (0 – 150)
6-volt lamp (automobile)
Two 110-volt lamps with sockets
Telephone receiver
110-volt supply of alternating current

Introduction. Alternating currents are now extensively used for lighting and power purposes. This is because of the economy of transmission of alternating currents, which has been made possible by a very simple and efficient machine known as a **transformer.** The essential parts of every transformer are two sets of coils linked by a common magnetic core of laminated iron.

The set of coils connected to the source of supply of alternat-

* This experiment is based on similar experiments in Ahrens, Harley and Burns' *Practical Physics Manual.*

ing current is termed the **primary**; while the set of coils connected to the load, such as a bank of lamps or a group of motors, is termed the **secondary**. The fundamental purpose of a transformer is to change the voltage. When the voltage on the secondary is *higher* than the voltage on the primary, the transformer is called a " step-up " transformer; and when the voltage on the secondary is *lower* than that on the primary, the transformer is called a " step-down " transformer. Thus it is common practice to transmit the alternating current about our streets at 2300 volts and then to use a transformer to " step it down " to 115 volts for use in lighting our houses.

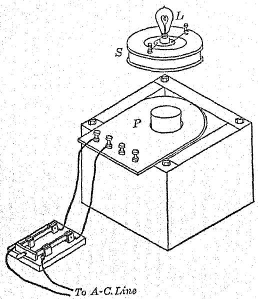


Fig. 103. What lights the lamp?

In this experiment we shall study some of the fundamental principles involved in the construction and operation of a transformer.

Directions. (*a*) Place the coil inside the laminated iron frame and slip the laminated iron core inside the coil. Connect the 110-volt alternating-current circuit to the primary coil (about 300 turns). Connect the 6-volt lamp to the secondary coil as shown in figure 103. Move the secondary coil up and down over the primary coil and record the distance between the two coils when the lamp begins to glow.* *How does the brightness of the lamp depend upon the distance of the secondary coil from the primary coil?*

If the primary current is alternating, how does the magnetic flux in the core change?

*Don't leave the current on the low-voltage winding longer than is really necessary because the coil may become over-heated.

What induces a current in the secondary coil? Is this secondary current direct (continuous) *or alternating?*

Why does the intensity of the secondary current depend upon the position of the secondary coil?

(*b*) A telephone receiver is a much more sensitive detector of induced currents than a lamp. Connect a telephone receiver across the secondary in place of the lamp and move the secondary coil about in the vicinity of the primary. *Record the greatest distance from the primary at which you can hold the secondary and hear a buzzing in the receiver. Why is the telephone receiver a more sensitive detector of electric currents?* (Investigate its construction.)

(*c*) *Do the primary and secondary coils of a transformer attract or repel each other?* Suspend the secondary coil by a spiral spring above the primary as shown in figure 104. Close the primary circuit and note carefully the effect on the secondary. Then break the primary circuit and note the result. In case you are in doubt as to just what happens, repeat the experiment several times. *Explain how this experiment illustrates Lenz's Law.*

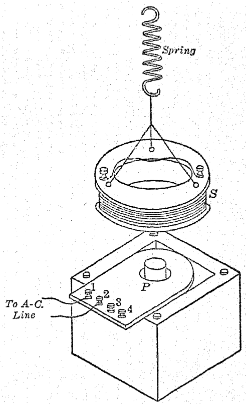


Fig. 104. Primary coil P attracts the secondary S.

(*d*) In a commercial transformer the primary and secondary coils are wound on the same iron core and the iron core is extended and bent around so as to form a closed magnetic circuit. In this way practically all the magnetic flux of the primary acts on the secondary and there is little or no magnetic leakage.

We may illustrate this by putting the coil and core inside the laminated iron frame, as shown in figure 105. Connect the high-voltage winding (600 turns) to the 110-volt alternating-current circuit. Connect the low-voltage winding (300 turns) to an a-c. voltmeter. *Record the voltage across the primary coil and that across the secondary coil. Compute the volts-per-turn in each coil.* This illustrates a step-down transformer.

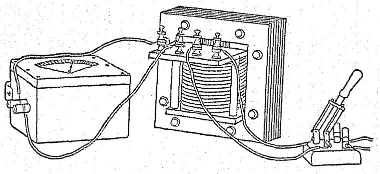


Fig. 105. Testing the voltage of a transformer.

(*e*) To illustrate the principle of a step-up transformer, connect the low-voltage winding (300 turns) to the 110-volt circuit and the high-voltage winding (600 turns) to two 110-volt lamps *joined in series.*

CAUTION. Remember that a 220-volt circuit is dangerous to handle! Don't turn on the current until the instructor has inspected and approved your connections. Always turn off the current while changing the connections.

We may measure the voltage across the terminals of the secondary coil by getting the voltage across each lamp and then adding the results. *Compute the voltage-per-turn in the primary coil and in the secondary coil.*

How do the voltages across the primary and secondary coils depend upon the number of turns in each?

What is the difference between a step-up and a step-down transformer?

Why can you not use a transformer on a direct-current circuit?

Optional experiment. The commercial transformer is usually made with the core in the shape of a rectangle and coils on opposite sides (core type); or with the core spreading out and dividing at the ends so as to form a closed magnetic circuit (shell type). With the working

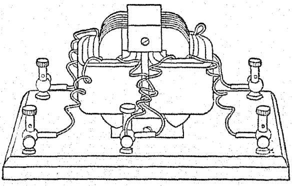


Fig. 106. Model transformer.

model shown in figure 106 each of the types may be illustrated and tested. *Why are there two primary coils and two secondary coils? How should they be connected?*

QUESTIONS AND PROBLEMS

1. In a step-up transformer is the energy delivered at the secondary greater than the energy received at the primary coils? Explain.

2. In a step-up transformer is the current induced in the secondary greater than that in the primary? Explain.

3. Is the primary current in a transformer zero when the secondary current is zero? Explain.

4. Why does a commercial transformer get hot? What means are employed for cooling transformers?

5. If 2300 volts are impressed on the high-tension coil (1860 turns), what will be the voltage across the low-tension coil (93 turns)?

6. A step-down transformer is used to change 2200 volts to 225 volts. If the primary winding has 1180 turns, how many turns will be needed for the secondary?

EXPERIMENT 51

REACTANCE AND IMPEDANCE

I. *How can we measure the impedance of a choke coil?*
II. *How does the impedance of a coil differ from its resistance?*
III. *How can we compute the reactance of a coil from its impedance and resistance?*

Coil with movable iron core	Alternating-current circuit (110-volt)
Bank of 4 lamps (50-watt)	Direct-current circuit (110-volt)
A-c. voltmeter (0 – 150)	Double-pole double-throw switch
A-c. ammeter (0 – 30)	

Introduction. We have already seen that the resistance of a coil to direct current can be measured by placing a voltmeter across the terminals of the coil to determine the voltage and by inserting an ammeter in the circuit to determine the current. Then the resistance

$$R \text{ (ohms)} = \frac{E \text{ (volts)}}{I \text{ (amperes)}}, \text{ according to Ohm's Law.}$$

This method can also be applied to an alternating-current circuit provided the circuit is non-inductive, that is, contains no coils of wire.

In an inductive circuit we find that there is something besides resistance which opposes the current. For example, if we connect a bell-ringing transformer to a 110-volt direct-current line, we find that 8.5 amperes flow through the primary; but when we connect it to a 110-volt alternating-current line, we find only 0.05 amperes to be flowing in the primary coil. The first experiment shows that the resistance is 13 ohms. The second experiment shows that there is something which greatly checks the alternating current, called **impedance.** In this case the impedance is $\frac{110}{0.05}$, or 2200, ohms.

This great difference is evidently not caused by any change in the primary coil but must be due to the alternating nature

of the current. An alternating current is always changing and on a 60-cycle line reverses 120 times every second. If the circuit consists of a coil, and especially if the coil contains an iron core, we find that it opposes a change in the current flowing. We may think of the magnetic field of every turn of the coil as cutting many adjacent turns and so causing a counter-electromotive force which at every instant opposes the change in current. This inductive resistance is called **reactance** (X). It depends upon the magnetic effect which the different parts of the circuit have on each other and also upon the frequency of the current.

In most a-c. machinery we have to consider a combination of resistance and reactance, and this apparent resistance we call the **impedance** of the circuit. It can be mathematically proved that the square of the impedance equals the sum of the squares of the reactance and the resistance. Therefore

$$\textbf{Impedance} = \sqrt{\textbf{Resistance}^2 + \textbf{reactance}^2}.$$

In this experiment we shall measure the impedance and resistance and shall then compute the reactance.

Directions. Connect a source of 110-volt direct current across one side of the double-pole double-throw switch and a source of 110-volt alternating current across the other side. Connect the bank of lamps in series with the choke coil to the center posts of the switch (Fig. 107).

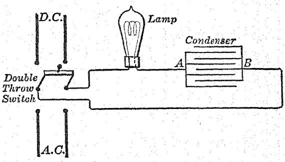


Fig. 107. Effect of condenser in d-c. and in a-c. circuits.

(a) Close the switch on the d-c. side. Observe the brightness of one lamp when the core is out of the coil and then when the core is entirely inside the coil. *How does changing the magnetic field of a coil connected to a d-c. circuit affect the current?*

(*b*) Close the switch on the a-c. side and then repeat the observations. *How does changing the magnetic field of a coil connected to an a-c. circuit affect the current?*

(*c*) Insert an ammeter to measure the current flowing through the coil and put a voltmeter in parallel with the coil to measure the voltage across its terminals. Close the switch on the d-c. side and insert enough lamps so that a large reading is available. Read both meters when the iron core is inside the coil and again when it is outside. *Compute the resistance of the coil.*

(*d*) Now close the switch on the a-c. side and read both meters when the iron core is inside the coil and again when it is outside. *Compute the impedance of the coil when the iron core is within.*

Compute the reactance of the coil from its impedance and resistance.

Optional experiment. Show the condition of resonance in an a-c. circuit by balancing the reactance of a choke coil with the reactance of a condenser. Connect five 2-microfarad condensers in parallel, thus making a 10-microfarad condenser. Connect the choke coil with core removed, the lamp bank (two 50-watt lamps), and the condenser all in series. Close the switch on the d-c. side. *Why does the direct current not flow?*

Close the switch on the a-c. side. *Why does the alternating current flow?* Note that the lamps are dimmed by the reactance of the condenser. Now insert the core into the coil and slide the coil and core part way into the iron frame. By trial a position of the coil in the frame will be found where the lamps glow brightly. This is the condition of **resonance** and is of great importance in radio circuits. This subject is explained more fully in Jackson and Black's *Elementary Electricity and Magnetism.*

QUESTIONS AND PROBLEMS

1. What advantages has a choke coil over a rheostat for current control?

2. How would you state Ohm's Law for a-c. circuits containing inductance?

3. The reactance X of a coil can be computed from the following equation:

$$X = 2\,\pi f L$$

where f = frequency and L = inductance in henrys. What would be the effect on the reactance of a certain coil if the frequency were changed from 60 to 25 cycles per second?

4. Suppose a circuit has a resistance of 10 ohms in series with an inductance of 0.1 henrys; the frequency of the alternating current is 60 cycles per second. Find the current which will flow when 100 volts is impressed on the circuit.

EXPERIMENT 52

VACUUM-TUBE RECTIFIER

What is the efficiency of a " Tungar " rectifier when used to charge a 6-volt storage battery?

Supply of 110-volt alternating current	D-c. ammeter (0 — 30)
Indicating wattmeter	D-c. voltmeter (0 — 15)
	Storage battery (6 volts)

Introduction. In certain applications of electricity it is necessary to have direct (or continuous) current; *e.g.*, for operating motion-picture projectors and magnetite arc lamps, for charging storage batteries or furnishing power for city transit systems, and for electro-chemical industries. When large quantities of a-c. power have to be changed to d-c. power, the rotary converter is employed. This apparatus consists of an a-c. motor coupled to a d-c. generator.

For converting small amounts of power there are various devices in use, such as the mercury-vapor rectifier, the electrolytic rectifier (so-called " Nodon valve "), the vacuum-tube (or Tungar) rectifier, and the vibrating rectifier.

In this experiment we shall study the Tungar rectifier as an example of the vacuum-tube type. The essential parts are a step-down transformer and a vacuum tube which contains a little argon (an inert gas). The tube also contains a tungsten spiral filament which, when incandescent, sends off electrons (negative electricity) and so ionizes the gas. But the current

flows through the bulb only in one direction, from the graphite anode to the filament. Thus the tube acts as a valve, allowing the alternating current to flow through it only in one direction; it produces unidirectional but intermittent current. The transformer steps down the voltage used across the filament and that used in charging the battery, as shown in figure 108. Since this rectifier acts as a half-wave rectifier, we must not expect high efficiency. Its convenience and low cost for maintenance have given it an extensive use in charging the storage batteries used for ignition and radio purposes.

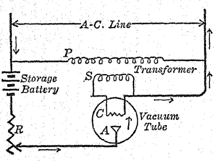


Fig. 108. "Tungar" rectifier used to charge a battery.

Since the current lags behind the voltage, we cannot measure the watts put into the rectifier by a voltmeter and ammeter, but must use a wattmeter. We can easily measure the output in watts by measuring the current with a d-c. ammeter and the voltage by a d-c. voltmeter and then

Output (watts) = **voltage** (volts) × **current** (amperes).

From this we compute the efficiency as the ratio of the output to the input and express the result as per cent.

Directions. Connect the wattmeter so as to measure the a-c. input. The instrument consists of two sets of coils, one stationary, which carries the full current, and another movable set, which consists of the potential coils and carries only a small current proportional to the voltage. The current terminals are large and metallic; the potential terminals are smaller and capped with some insulating material. Therefore connect the wattmeter with the current terminals inserted *in* the line, just as you would an ammeter, and with the potential terminals *across* the line, just as you would a voltmeter.

In connecting the storage battery to the rectifier, be sure to connect the positive terminal (red) to the positive (+) terminal

of the battery. Insert the d-c. ammeter in the line so that the current enters the ammeter at the + binding post. The voltmeter is connected across the terminals of the battery. When everything is connected as shown in figure 109, have the instructor approve your apparatus.

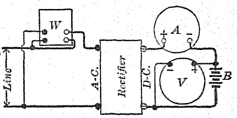


Fig. 109. Measuring the efficiency of a rectifier.

Turn on the current and read the meters at intervals of 5 minutes for half an hour. *Compute the output in watts and the efficiency in per cent. Find the average efficiency.*

Optional experiment. Make a similar test of the efficiency of another kind of rectifier. Compare the two rectifiers as to first cost, efficiency, and maintenance.

QUESTIONS AND PROBLEMS

1. Why would you expect the efficiency of such a rectifier to be less than 50 per cent?

2. How would you determine the amount of energy used to operate the wattmeter?

3. Why does the Tungar rectifier make a humming noise when in operation?

4. In testing a certain rectifier it was found that 320 watts were taken from the a-c. line and a current of 1.70 amperes at 85.0 volts was being delivered to the battery. Compute the efficiency of the rectifier.

5. If this apparatus (problem 4) remained in operation under the same conditions for 15 hours and 15 minutes, how much did the electricity delivered to the battery cost? Assume that the electricity received from the a-c. line cost 10 cents per kilowatt-hour.

SOUND

EXPERIMENT 53

FREQUENCY OF A TUNING FORK

How many vibrations does a tuning fork make in one second?

Tuning fork with stylus attached
Recording apparatus (Fig. 110)
Glass plates
Clock or stop watch
Gum camphor
Clamp for releasing tuning fork

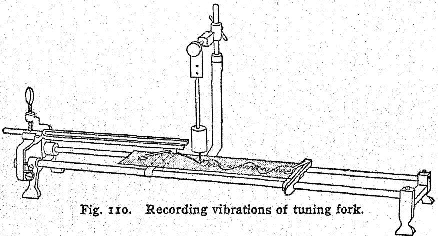


Fig. 110. Recording vibrations of tuning fork.

Introduction. Since a tuning fork, which gives a musical sound, vibrates too fast to be counted directly by the eye, it is necessary to use a special apparatus, such as is shown in figure **110.** This very simple *chronograph* consists of three parts: a smoked glass plate or paper,* a tuning fork with a fine-wire

* If the tracings are made on smoked paper, they may easily be "fixed" by pouring over the smoked surface a very thin solution of shellac. After a few minutes the paper is dry and may be pasted in the notebook as a part of the record of the experiment.

Since smoked glass is always more or less dirty, the glass is sometimes covered with a thin coat of whiting in alcohol or of "Bon ami" soap.

or paper stylus attached to one prong, and a short pendulum which also has a wire stylus projecting so as to touch the glass plate. The smoked-glass plate is drawn along in a straight line beneath the stylus of the vibrating tuning fork and at right angles to the direction of the vibrations so that it makes a wavy curve on the glass, and at the same time the pendulum point vibrates back and forth across this curve. If, then, we know the number of vibrations of the pendulum per second, we can easily count on the smoked glass the number of vibrations of the fork corresponding to one complete swing of the pendulum, and thus compute the number of vibrations of the tuning fork per second.

Directions. Clamp the tuning fork so that its tracing point is only a few millimeters from the point of the pendulum. The line of these two tracing points should be parallel to the direction in which the glass is to move. The tracing points must rest lightly on the smoked-glass surface and yet hard enough to scratch away the coating. To test this, set the fork and pendulum in vibration with the glass at rest. A good way to set the fork vibrating is to squeeze the prongs together with a little U-shaped metal clamp and then quickly pull the clamp off.

To get the rate of the pendulum, set it swinging and count the number of vibrations which it makes in one minute. *Compute the number of vibrations of the pendulum per second.*

To smoke the glass plate, hold it in the flame of burning gum camphor. Keep the plate moving back and forth so as not to crack it by overheating. Place the plate, smoked side up, on the slider and adjust the two styluses.

When the apparatus is properly adjusted, start the pendulum swinging, set the fork vibrating, and then draw the glass along the track at such a rate as to have at least one *complete* swing of the pendulum recorded on the glass. Several sets of tracings may be recorded on the same plate by moving it a little to one side and so bringing a fresh surface under the tracing points.

Next count the number of vibrations of the fork corresponding to a full vibration of the pendulum, *i.e.* the number of vibrations traced by the fork between the points A and C (Fig. 111), or between B and D, estimating in every case to tenths of a vibration.

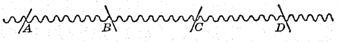


Fig. 111. Curves of tuning fork and pendulum.

Make at least three tracings and on each tracing count the number of vibrations of the tuning fork corresponding to a complete vibration of the pendulum. *Take the mean of these counts as the number of vibrations of the fork to one of the pendulum.*

Compute the number of full vibrations made by the tuning fork per second.

Optional experiment. Determine the pitch of a given musical sound, such as that of an organ pipe or a tuning fork, by means of a siren disk.* The disk may be rotated by a variable-speed electric motor and its speed measured. Then by blowing a blast of air through a row of holes in the disk, a musical tone can be produced which has the same note as the given musical sound. The vibration frequency of the tone can be computed by multiplying the number of holes in the circle by the number of revolutions per second.

QUESTIONS

1. In this experiment what is the effect on the curve traced if we move the smoked plate more rapidly?

2. Why is it essential to have the stylus of the pendulum close up to the stylus of the tuning fork?

3. Why is the number of vibrations of the tuning fork between A and B not necessarily equal to the number between B and C?

4. What do you think your probable error is in timing the pendulum?

5. What note on the piano scale corresponds most closely with the vibration frequency of the tuning fork as determined?

*For a more complete description of this experiment see pages 81–82 in John C. Packard's *Everyday Physics*.

EXPERIMENT 54

WAVE LENGTH. VELOCITY OF SOUND IN AIR

I. *How long is the sound wave emitted by a vibrating tuning fork?*
II. *How fast does the sound wave travel in the air of the room?*

2 Tuning forks of known frequency but of different pitch (256, 512)	Large flat cork
	Meter stick
Hydrometer jar of water	Rubber bands
Resonating tube	

Introduction. If a tuning fork is set in vibration and held over a column of air, the loudness of its note will be greatly increased provided that the air column is of such a length as *to vibrate in sympathy* with the fork. Such an air column is said to be in **resonance** with the fork. Examples of the use of resonant air columns are to be found in fifes, trombones, cornets, and organ pipes.

This phenomenon may be explained on the theory of the combination of direct and reflected waves. Suppose a prong of the fork begins to move *downward.* It starts a wave (condensation) down the tube. If this impulse, or wave, can travel down to the bottom and back again just in time to meet the prong as it starts to move *upward,* then the two waves combine and produce a louder tone. Since this condensation has traveled to the bottom of the air column and back during a half vibration of the tuning fork, the distance up and down must be equal to half a wave length, or *the distance one way is equal to a quarter of a wave length.* Experiments show that the distance actually traveled by the impulse in going each way is a little greater than the length of the air column on account of the reflection from the sides and the spreading at the open end. The correction to be added is equal to about one quarter of the inside diameter of the tube. Therefore the length of the sound wave emitted by the tuning fork is four times the sum of the air column and one fourth of its diameter.

This wave length multiplied by the number of vibrations per second (Exp. 53) gives the distance which the sound travels in the air in one second at the temperature of the room.

Directions. Place the resonating tube in the hydrometer jar and pour in water so as nearly to fill the jar. Strike one prong of the tuning fork on a large cork stopper and hold the vibrating fork over the open end of the tube, as shown in figure 112. By raising the tube slowly out of the water, a point will be found where the air column is of just the right length to reënforce the fork. Mark with a rubber band around the tube the position of the water where the sound was loudest. Then set the fork in vibration again and by raising and lowering the tube and listening intently, determine again as precisely as you can the point where the air column gives the greatest reënforcement. Measure the length of the air column.

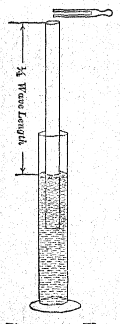


Fig. 112. Wave length of a fork.

In this experiment the settings for obtaining the data are more or less indefinite and therefore one trial may be far from the true value. To reduce the probable error make several trials and take the mean. Experience has shown that a more accurate setting can be obtained if the tube is moved up and down rather rapidly through the position of maximum resonance, while the extent of the movement is gradually reduced until the position of maximum intensity is found.

The length of the air column (plus about 0.25 of the internal diameter of the tube) is equal to *one fourth* the wave length of the tone of the fork in air. *Compute the wave length of the sound emitted by the tuning fork.*

Given the frequency of the fork, *i.e.* the number of vibrations per second, *compute the velocity of sound at the temperature of the room*, using the wave length just determined.

If time permits repeat the experiment, using a tuning fork of some other frequency.

It is also possible to find a second position of the water surface nearer the bottom of the tube which also gives reënforcement to the sound. The difference between the length of the short and long air columns is equal to *one half* a wave length.

It is usually stated that the velocity of sound in air is 331 meters per second at 0° C. and that it increases about 0.6 meters per second for each degree C. rise. Compare this calculated value for the velocity of sound with the result of your experiment and compute the percentage error.

Optional experiment. The speed of sound in air may be measured out of doors by repeating the experiment described in section 387 of Black and Davis' *Practical Physics — Revised.* Use a toy cannon and a stop watch. Get the distance from a large scale map of the region. Record the temperature.

QUESTIONS AND PROBLEMS

1. If the resonant tube is long enough, a second position will be found where the fork is reënforced. Show that this longer air column is $\frac{3}{4}$ of a wave length.

2. What is the pitch of a closed organ pipe 62 centimeters long on a day when the temperature is 20° C.?

3. If the temperature drops to 0° C., what change will be produced in the pitch of the organ pipe in problem 2?

4. Which pipes produce the high notes in a pipe organ?

5. If the frequency of a tuning fork is 435 vibrations per second, what length of air column (expressed in inches) would reënforce the fork when the temperature was 20° C.? (Velocity of sound in air is 1087 feet per second at 0° C. and increases 2 feet per second for each degree C. rise.)

EXPERIMENT 55

VIBRATING STRINGS

I. *How is the rate of vibration of a stretched wire affected by its length?*

II. *How is the rate of vibration of a stretched wire affected by the tension?*

Sonometer with two or more wires
3 Tuning forks (C, G, and C')
2 Spring balances or pulleys with weights
Meter stick

Introduction. We are all more or less familiar with certain stringed musical instruments, such as the violin, the harp, and the piano. The violin has four strings, three made of plain gut and the fourth of gut wound with fine wire. The violinist changes the length of the vibrating string with his fingers and in the preliminary tuning of the instrument he adjusts the tension on each string. Thus by applying a few simple physical principles in regard to vibrating strings he is able to produce a marvelous variety of musical tones. In this experiment we shall learn how the pitch of the musical note produced by a vibrating string depends upon its length and its tension.

Directions. I. ***Effect of length.*** Stretch a steel wire (about 26 B. & S.) along the sonometer board (Fig. 113) and move the bridge B so that the distance from the fixed end A is about 60

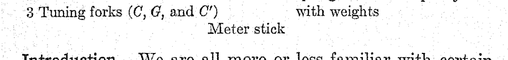


Fig. 113. Sonometer with two strings.

centimeters. Adjust the tension on the wire until the note given by the wire when plucked in the middle is in unison with the note of the lowest fork (middle C).

This unison can best be detected by the absence of **beats.** When two notes are nearly but not quite in unison, they at

one moment reënforce and at the next oppose each other, and the sound is alternately loud and faint. These pulsations, known as beats, furnish a mechanical method of securing unison. The beats cannot be detected until the wire and the fork are nearly in unison; but when once detected, the length of the wire should be varied so as to make the beats succeed each other more and more slowly until finally they seem to disappear. The sound of the fork may be greatly reënforced by holding its shank on the sonometer board. Then the beats can be felt by resting the fingers lightly on the board.

(*a*) Measure carefully the length of the wire between A and B. Record the pitch of the tuning fork (the letter or number).

(*b*) Keeping the tension on the wire the same, move the bridge B until the note of the vibrating wire AB is exactly in unison with the fork C', which is an octave higher than the first one. Measure the length of the vibrating wire between A and B. Record this with the pitch of the fork.

(*c*) Again vary the length of the vibrating wire so as to bring it into unison with a third fork, such as G, the fifth note above middle C. Measure and record.

Compare the measured lengths of the vibrating wire with the vibration numbers as marked on the forks. State the law concerning the rate of a vibrating string and its length when the tension is kept constant.

II. ***Effect of tension.*** Stretch two wires of the same size and material on the sonometer (or place two boards side by side). Put the bridge B at the same distance from A (about 60 centimeters) for each wire. Adjust the tension in each wire so that the plucked wire gives a musical note at about middle C. Take great care to bring the two wires into exact unison by adjusting the tension. Record the tension on one of the wires by counting the weights or reading the spring balance.

(*a*) Move the bridge under the second wire so that the vibrating portion is only half as long as at first. Then increase

the tension on the first wire, leaving its length exactly as at first, until it is in unison with the shortened wire. Record this tension on the tightened wire.

What is the ratio between the tension on the wire at first and the tension after tightening? What is the ratio between the vibration rates in the two cases? In order to double the rate of vibration, how many times must we multiply the tension?

(*b*) Again move the bridge under the second wire so that it is only two thirds its original length; but keep the tension on this wire constant. Adjust the tension on the first wire so that the two are in unison. Record this value of the tension.

Compare the vibration rates of the wire as stretched at first and as stretched now. Compute from the law suggested in (a) the tension which might be expected in (b). Compare the calculated tension with the observed tension.

Optional experiment. Determine the effect upon the pitch of a vibrating string of a variation in the diameter of the string. Measure with a micrometer caliper the diameter of the wire used on the sonometer and then measure the diameter of a larger wire (twice the diameter). Adjust the tension on the first wire until it is in unison with the fork C; then make the tension on the larger wire the same value. Now move the bridge under the larger wire until it vibrates in unison with the first wire. Measure the length of the vibrating portion of the larger wire. *Compute its rate if it were as long as the first wire* (*Law of Lengths*). *State a law connecting the diameter of a string with its rate of vibration, when length and tension remain fixed.*

QUESTIONS AND PROBLEMS

1. What is the quickest way of raising the pitch of a violin string?

2. How does a piano tuner adjust the pitch of a certain key?

3. Why are the wires of the low notes of a piano wrapped with wire?

4. If a wire under a tension of 7.5 pounds gives a certain note, how much higher would the note become on increasing the tension to 30 pounds?

5. How could you change the length of the wire used in problem 4 to produce the same change in pitch?

LIGHT

EXPERIMENT 56

BUNSEN PHOTOMETER

I. *What is the candle power of a given electric-lamp bulb in terms of a standard lamp?*

II. *What is the commercial efficiency of the lamp?*

III. *What is the effect on the downward intensity of an electric lamp of adding a shade?*

Bunsen photometer in a darkened room or in a light-tight box
Two incandescent lamps (one of known candle power)
Voltmeter (0 – 150 volts)
Ammeter (0 – 3 amp.)
Shade for electric bulb

Introduction. The problem of the proper illumination of our streets, factories, and homes is of vital importance; but it is by no means a simple one. To get sufficient light of the right color without a glare and at a reasonable expense is the desideratum. The first factor to be considered is the **luminous intensity** of the lamp itself. We must have a **standard lamp** as a basis of comparison. The oldest standard lamp (still used in calculations) is the English standard candle. The illuminating power of a horizontal beam from this candle is called a **candle power.** In this country the standard is fixed by a set of incandescent lamps maintained at the Bureau of Standards in Washington, D. C. The unit of intensity is called the **international candle.**

The instrument used to compare a standard lamp with some other whose intensity is desired is called a **photometer.** In this experiment we shall use a Bunsen "grease-spot" photom-

eter because it is very simple and easy to operate. Essentially it is a white paper screen with a translucent spot in the center. This screen is placed between the lamps to be compared so that one side is lighted by one lamp and one by the other. The screen is moved back and forth between the lamps until it is equally illuminated on both sides. In this position the spot disappears, or at least looks equally bright on each side.

Experience shows that the illumination of a book decreases as one moves away from the lamp. In fact it can be proved that the intensity of illumination varies inversely as the square of the distance. Thus a 16-candle-power lamp will illuminate a surface placed 1 foot from it with an intensity of *16 foot candles*. But if the book were 2 feet from the lamp, the intensity of illumination would be $\frac{16}{4}$, or 4, foot candles. In general,

$$\textbf{Illumination (foot candles)} = \frac{\text{candle power}}{\text{distance squared (ft.)}^2}.$$

Suppose that the lamp X (Fig. 114) to be tested is A feet from the screen of a Bunsen photometer, and that the standard

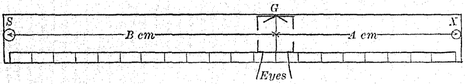


Fig. 114. Diagram of a Bunsen photometer.

lamp S equally illuminates the screen when B feet away.

Then
$$\frac{X}{A^2} = \frac{S}{B^2}$$
or
$$\frac{X}{S} = \frac{A^2}{B^2}.$$

Stated in words, *the candle powers of the two lamps are directly proportional to the squares of their distances from the screen.* Thus, knowing S and measuring A and B, we can compute X.

Directions. Set up a Bunsen photometer in a darkened room or in a light-tight box, as shown in figure 114. Use a standard electric lamp S as a basis for comparison. Insert a

rheostat in the power circuit so as to bring the standard lamp to its required voltage. At the other end of the photometer bar (about 200 centimeters from the first lamp) set up another electric lamp X which is to be tested. Between these two lamps place the photometer box or screen G with the grease spot. This screen is to be moved back and forth between the lights until a position is found such that the screen is equally illuminated on both sides; that is, such that the central spot or disk and the surrounding rim of paper are of the same brightness. Since it is difficult to set this sight box or screen precisely right, several trials should be made and the average position taken.

Find the candle power of an ordinary tungsten (Mazda B) *lamp;* that is, the **mean horizontal candle power.** From the readings of the voltmeter and ammeter in the lamp circuit, *compute the watts per mean horizontal candle power* (commercial efficiency). *Compute the cost of maintaining such a lamp for one hour and the cost per candle-power hour.* (Unless otherwise directed, assume that electricity costs 10 cents per kilowatt-hour.)

Finally, turn the incandescent lamp into a horizontal position and *measure its candle power downward both with and without a shade.*

If time permits, measure the candle power of a gas-filled tungsten (Mazda C) lamp and *compute its commercial efficiency.*

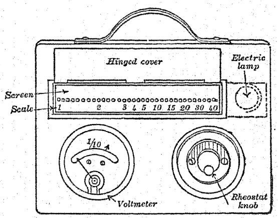


Fig. 115. A foot-candle meter.

Optional experiment. If a portable photometer (a foot-candle meter, figure 115) is available, measure in foot candles the illumination received on your desk in the evening. Measure the illumination of an electric lamp at some point directly under

it, and then, knowing the distance, compute the candle power of the lamp in that direction. Measure the candle power of an automobile headlight straight ahead.

QUESTIONS AND PROBLEMS

1. Why is illumination in a shop or factory such an important matter?
2. How would you compare the cost of lighting by gas and by electricity?
3. Why are the modern tungsten (Mazda) lamps so much more efficient than the carbon-filament lamps?
4. If a 25-watt "Mazda" lamp has an efficiency of 1.15 watts per candle power, (*a*) what is its candle power? (*b*) what is the cost of the electricity needed to light the lamp for 1000 hours? (Assume that electricity costs 10 cents per kilowatt hour.)
5. A foot-candle meter indicated 3 foot candles when held 5 feet from a lamp. What is the candle power of the lamp?

EXPERIMENT 57

IMAGE IN A PLANE MIRROR

I. *How does the angle of incidence compare with the angle of reflection?*

II. *How does the image in a plane mirror compare with the object in respect to size, form, and distance from the mirror?*

Plane mirror	Paper
Block for holding mirror with rubber bands	Protractor
	Ruler
Block with vertical black line on one face	

Introduction. The ancients used mirrors which consisted merely of brightly polished metallic surfaces. Most of the mirrors which we use are made of glass coated with a layer of metal on the back side. In this way the metallic surface remains bright.

Have you ever stopped to think where your image appears to be as you looked into a mirror? Does it seem to be on the glass, behind the mirror, or in front of the mirror? Perhaps

you have used a small mirror to reflect the sunlight into someone's eyes. Do you know just how to place your mirror in order to reflect the light in any particular direction? Doubtless you have read about the use of the periscope in warfare. Did you know that it consists essentially of two plane mirrors placed in a certain way in a tube?

In this experiment we shall learn just how a plane mirror reflects light and just where the image seen in such a mirror appears to be.

Directions. I. ***Reflection in a plane mirror.*** Draw a straight line across the middle of a sheet of paper and label this the *Mirror Line.* Set up the mirror so that its reflecting surface is exactly over this line. At a distance of 10–15 centimeters in front of the mirror, make a dot and label it O. Place the small block with its vertical black line standing directly over this dot. To locate the image of this line, lay a straightedge on the paper so that it points directly at the image. Care should be taken *to sight* with only one eye along the edge of the ruler and then draw a clean sharp line along this edge that points toward the image. To make sure that the ruler has not slipped in this process, remove the ruler and look along the surface of the paper to see if the line really does point at the image. If not, erase the line and try again.

Place the ruler on the other side of the small block and draw another *sight line* just as before, making sure that the mirror still has its reflecting surface just on the mirror line. Repeat this process, drawing several sight lines.

Remove the mirror and block and continue each of the sight lines as solid lines up to the mirror line and then continue them as dotted lines behind the mirror until they meet. Mark this point of intersection I, the image-point. The solid sight lines represent **reflected rays.** From the object-point O draw lines to the intersection of each of these sight lines with the mirror line. These lines from O to the mirror represent the **incident rays.** Connect the object-point O with the image-

point I, making the line solid in front of the mirror and dotted behind the mirror. Indicate the direction in which light travels along the lines by arrows, as shown in figure 116 (a).

At one of the points of reflection erect a **normal**, that is, a perpendicular to the mirror; label the angle between the incident ray and the normal the **angle of incidence**, and the angle between the reflected ray and the normal the **angle of reflection**. Take the following measurements:

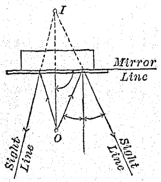


Fig. 116 (a). Image of a point.

Distance of object from mirror	. . . .	cm.
Distance of image from mirror	. . . .	cm.
Angle between OI and the mirror line	. .	°
Angle of incidence	. . . .	°
Angle of reflection	. . . .	°

From these data *make a general statement in regard to the distance of the object from a plane mirror and its corresponding image distance; also in regard to the angle of incidence and the angle of reflection.*

II. ***Image in a plane mirror.*** On another sheet of paper draw a line across the middle and set up the mirror as before. Draw a triangle (about 5 cm. on each side) and label it ABC, as shown in figure 116 (b). Locate by drawing two sight lines at each point, the image-points of A, B, and C, and label these points A', B', and C'. Construct with dotted lines the image of ABC. Measure the lengths of $A'B'$, $B'C'$, and $A'C'$ and compare them with the corresponding object-lines. If the paper is folded along the mirror line and if the work has been carefully done, the image will be found to coincide very closely (within 1 or 2 mm.) with the object when the paper is held to the light. If the first trial is not satisfactory, repeat the experiment.

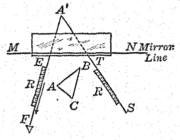


Fig. 116 (b). Image of a triangle.

Compare the object with its image in a plane mirror in respect to size, distance, and form.

Optional experiment. Some very curious effects can be produced by using two or more plane mirrors and so producing double or triple reflections. Set up two plane mirrors so as to form a right angle (Fig. 117). Locate by sight lines the position of the three images of any object placed in the open space between the mirrors. Move the mirrors so as to form an angle of 60°, and count the number of images; then make an angle of 45° and count the number of images. *State a rule which will tell you the number of images formed for two mirrors at any angle.*

Set up two plane mirrors in such a way as to illustrate the principle of the periscope.

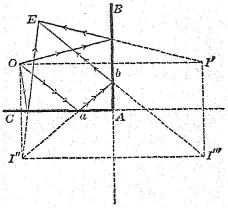


Fig. 117. Reflection in two mirrors.

QUESTIONS

1. A man approaches a mirror at a certain speed and finds that he is approaching his image at double the speed. Why?

2. A boy with the letters *R. L. S.* on his sweater stands in front of a plane mirror. Draw the letters as they appear when seen in the mirror. Explain.

3. A girl 5 feet tall finds that she can see her entire image in a plane mirror 2.5 feet long. How must the mirror be placed?

4. What do you really mean when you say an image is "behind a mirror"?

5. If a plane mirror is rotated through a certain angle, how much is the reflected ray turned? Assume that the incident ray has a fixed direction.

6. What is a plate-glass mirror? Why is it so expensive?

EXPERIMENT 58

IMAGES IN CYLINDRICAL MIRRORS

I. *What is the position, size, and shape of an image formed in a convex mirror?*

II. *What is the position, size, and shape of an image formed in a concave mirror?*

Convex-concave cylindrical mirror	Ruler
Paper	Pins

Introduction. Curved mirrors may be divided into two classes, **convex mirrors**, which bulge out in the middle, and **concave mirrors**, which cave in at the middle. The mirrors attached to the windshields of automobiles are usually convex, and the mirrors used behind the headlights are concave. If a lamp is placed in front of a concave mirror at a certain position, called the **principal focus**, the light is reflected as parallel rays. The distance of the principal focus from the mirror is called the **focal length** of the mirror. If the mirror is spherical, that is, part of the inside surface of a hollow sphere, then it can be shown that this *focal length is almost one half the radius of curvature.* If the lamp is placed nearer to the mirror than the principal focus, then the reflected rays are divergent; and if the lamp is placed further from the mirror than the focus, then the reflected rays are convergent. In this experiment we shall see just where the reflected rays converge to a point, called the image point. We shall also learn much about the size and shape of the images formed by both concave and convex mirrors and why each type of mirror is especially well adapted for certain purposes.

The principles involved in curved mirrors can be conveniently studied in cylindrical mirrors. In this experiment we shall stand the cylindrical mirror so that its straight edges are vertical and its curved edges are parallel with the table. The

mirror itself is merely a section of brass pipe nickel-plated, so as to serve both as a concave and a convex cylindrical mirror.

Directions. I. ***Convex mirror.*** Place on a sheet of paper a convex cylindrical mirror so that its straight lines are vertical, and then trace on the paper the position of its convex surface. About 5 centimeters in front of the mirror draw as object an arrow 6 centimeters long and label it ABC, as shown in figure 118. To locate the position of the image of A, place a pin at point A so that it stands erect and then draw two sight lines along the edge of a ruler (one on each side of the pin) pointing at the image of the pin. Label each of these lines A. Then stand the pin at B and draw, as before, two sight lines toward the image. In the same way draw sight lines to locate the image of C.

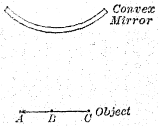


Fig. 118. Convex mirror.

Remove the mirror and pin; continue each pair of sight lines until they intersect. In this way locate the image-points of A, B, and C and label these points A', B', C'. Draw a straight line from A' to B', and from B' to C' with an arrow-head at A'. Label this arrow the **Image.**

Draw a dotted line from A to A', from B to B', and from C to C'. Prolong these lines until they intersect.

Compare the object and its image in a convex mirror as to position, size, and shape.

II. ***Concave mirror.*** Stand the mirror a little above the middle of a sheet of paper and draw a sharp line along its concave edge. Remove the mirror and draw a dotted line connecting the ends of the arc. Draw a perpendicular at the mid-point of this chord and label it **axis.** Assuming that the radius of curvature is 5 centimeters, mark the **center of curvature** with the letter C. Mark the **focus** F, which is halfway between the center of curvature C and the mirror M, as shown in

figure 119. In order to locate the images of objects at varying positions along the axis, draw a short arrow between F and M and label it A, another between F and C and label it B, and a third beyond C and label it D, somewhat as shown in the figure.

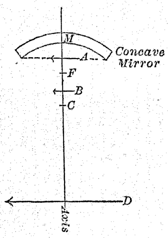


Fig. 119. Concave mirror.

Replace the concave mirror on its line and observe the direction, curvature, and relative length of the images of A and B. In order to see these images more distinctly, it will be useful to draw an arrow on a small strip of paper and fold up one end so that the arrow is on the vertical part, as shown in figure 120, and then place this strip of paper over A and B. *Do the images of A and B point in the same direction as the objects?*

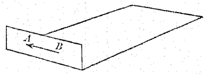


Fig. 120. Arrow on paper.

To locate the position of the image of A, stand a pin upright at the mid-point of A and draw two sight lines directly at its image. Label these lines A, A. Locate the images of B and D in the same way.

When an image seems to be back of a mirror, it is said to be **virtual**, because the rays of light do not actually come from the image-point but simply look as if they had come from it. On the other hand, when as in some cases with a concave mirror the image is found in front of the mirror, it is said to be a **real image** because the rays actually do pass through the image-point.

Fold up these two sheets of paper and glue them into your notebook as a part of your record of the experiment.

Make clear, concise statements in answer to the following questions:

(1) *Where must the object be placed in order to get a virtual image and where to get a real image?*

(2) *Where must the object be placed in order to get an image pointing in the same direction as the object and where to get a reversed image?*

(3) *Where must the object be placed in order to get an image which is smaller than the object and where to get a larger image?*

Optional experiment. Measure the focal length f of a small concave spherical mirror by getting the image of the sun upon a narrow strip of paper held in front of the mirror. The focus is the place where the spot of light is smallest and brightest.

Place in a darkened room a small electric lamp at a distance about three times the focal length from the mirror and find the position of the image by letting it fall on a cardboard screen. Measure the distance of the object from the center of the mirror D_o and the corresponding distance of the image D_i. *Compute the focal length f from the equation*

$$\frac{1}{f} = \frac{1}{D_o} + \frac{1}{D_i}.$$

Compare this value of the focal length with that obtained by using the sun as the object.

QUESTIONS

1. In what way does one's face appear distorted when seen in a convex cylindrical mirror?

2. How could you determine geometrically the center of curvature of a cylindrical mirror?

3. What sort of curved mirror would be best adapted for shaving? Why?

4. How does the image seen in a convex spherical mirror differ from that seen in a convex cylindrical mirror?

5. Why are the concave mirrors used in automobile headlights parabolic instead of spherical?

EXPERIMENT 59

REFRACTION OF LIGHT BY GLASS

I. *How is a ray of light bent in passing from glass into air?*
II. *What is the relation between the speed of light in air and in glass?*

Rectangular glass plate	Protractor
Paper	Pins
Ruler	Millimeter paper scale

Introduction. Optical instruments play a very important part in our modern life. The human eye is a most remarkable, though often imperfect, optical instrument. Our eyes are aided in their work by the microscope, the telescope, the camera, the stereopticon, and the motion-picture machine. In all the optical instruments mentioned we find lenses and in some of them also prisms. But to understand how these optical instruments work, we must first study the path of a ray of light through lenses and prisms; that is, the **refraction** of light by glass.

We all know that a stick standing obliquely in water appears to be broken at the water's surface; and we are familiar with the shoaling effect of water which makes a rock or a fish in the water always seem to be nearer than it really is. These phenomena are but examples of the refraction, or bending, of light as it passes from water into air.

The reason for the refraction of light was not understood until the velocity of light in different substances had been measured. In this experiment we shall learn how to determine the amount that a beam of light is bent in passing from glass or water into air by means of the velocities of light in the two media.

Directions. Lay a rectangular glass plate on a sheet of paper in the position shown in figure 121 and trace with a sharp pencil the edge of the glass. Stand a pin upright at A, touching the edge of the glass.

If one places his eye on a level with the paper and looks *into* the edge DE, the portion of the pin A seen through the glass seems to be in line with the part seen over the glass *only* when the eye looks into the glass in the direction FD, perpendicular to the edge DE.

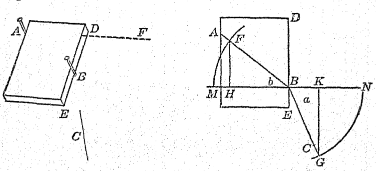


Fig. 121. Refraction by a rectangular plate of glass.

In order to show just how much a ray of light is bent in passing from glass to air, place a second pin B close to the edge DE as shown in the figure. Now move the head slowly to the left until the pin B just covers the image of pin A seen through the glass. Place a ruler so that one edge points directly at B and the image of A seen through the glass, and then draw the sight line C.

Remove the glass and connect the points A and B; this line represents the direction of a ray of light through the glass. Prolong the sight line until it strikes the point B. This sight line shows the direction of the ray AB after leaving the glass. If we erect a normal MN at B perpendicular to DE, *what do we find in regard to the size of the angle in air and the angle in glass?*

Index of refraction. The refraction of light in passing from glass into air depends on the relative speeds of light in glass and air. It has been proved (section 455 in B. & D.) that *the speed of light in air is to the speed in glass as the* ***sine of the angle*** *in air is to the* ***sine of the angle*** *in glass.* The term sine is the mathematical name for the ratio of the opposite side to the

hypotenuse of a right triangle.* Thus the sine of angle a is GK/BG. To get the ratio of the sines of these angles, lay off on AB and BC equal distances (the longer the better), such as BF and BG, and draw FH and GK perpendicular to the normal MN. The sine of angle a is GK/BG and the sine of angle b is FH/BF, but since $BF = BG$,

$$\frac{\text{sine } a}{\text{sine } b} = \frac{GK}{FH}.$$

In short, to get the **index of refraction** of the glass used in this experiment, *i.e., ratio of speed of light in air to speed of light in glass*, we have merely to divide the length of GK (measured to tenths of a millimeter) by the length of FH.

To make a second trial, move the position of pin A to a new point A' along the edge of the glass and repeat the experiment.

It is also interesting to measure angles a and b in degrees with a protractor and compute the index of refraction from the values of the sines given in the Tables in the Appendix.

Optional experiment. Find the shape of the path followed by a ray of light in passing from an object through a prism to the eye. Set up two pins A and B in a sheet of paper and place a triangular block of glass EFG as shown in figure 122. Sight along a straight edge in the direction CD, so that the two pins appear to be in line when seen through the side EG of the prism.

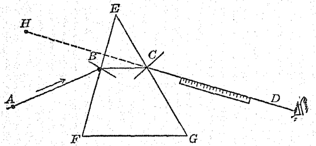


Fig. 122. Refraction by a prism.

Remove the prism and draw the line BC, the path of the ray through the prism. Construct perpendiculars at B and C to the refracting surfaces. *Describe the refraction of the ray on entering the prism and on leaving it. How much was the ray deviated from its original course? Is this angle of deviation constant?*

* For further information about sines and tangents of angles see Appendix.

QUESTIONS

1. Under what conditions is the angle of refraction greater than the angle of incidence?

2. What effect is produced on a ray of light in passing obliquely through a plate-glass window?

3. The index of refraction from air into water is 1.33. Does this mean that water refracts light more or less than glass? Explain.

4. What is meant by saying that the index of refraction is a physical constant?

5. Suppose a ray of light in passing from water into air is refracted so that the angle of refraction is 90°. The angle of incidence is called the critical angle. How much is the critical angle for water? (Two methods: construction and by table of sines.)

EXPERIMENT 60

FOCAL LENGTH AND CONJUGATE FOCI OF A CONVERGING LENS

I. *How far is the picture of a distant object from a convex lens?*
II. *What relation exists between the object-distance and the image-distance when the object is near a convex lens?*

Meter stick and supports (Fig. 124)	White cardboard screen
Electric or gas lamp in a metal box with wire netting	Holders for lens and screen
	Double convex lens (f. 10–15 cm.)

Introduction. Lenses may be divided into two classes: **concave** lenses, which have thick edges, and **convex** lenses, which have thin edges. Of these the kind which is most commonly used in cameras, telescopes, and microscopes is the convex lens. This type is often referred to as a *converging* lens because parallel rays are converged to a fixed point, called the **principal focus.** Some of us have doubtless handled a "burning glass" (a double convex lens) in such a way that the rays from the sun entered the lens and were so bent in

direction (refracted) that they converged to a point. To understand this phenomenon we may think of two glass prisms placed with their bases together. Parallel rays passing through these prisms will be bent toward the thick end of each prism, as shown in Experiment 59. A double convex lens is not very different in shape from this combination of prisms, except that its surfaces are spherical instead of flat.

The distance between the principal focus and the lens is the **focal length** of the lens. An object which is 100 feet or more away sends to a lens rays that are practically parallel; that is, rays from any distant object-point to different parts of the lens are very nearly parallel. Therefore we may locate the focus by getting the picture of a distant building or tree on a screen; we can then determine the focal length of the lens by measuring the distance between the lens and the image formed of the distant object.

When the object is placed nearer the lens but beyond the focus, the image is formed at a definite point (depending on the focal length) *beyond* the focus on the other side of the lens. In this experiment we shall see that whenever a real image is formed on a screen, then the object and image may be interchanged. Two such points situated on either side of a lens so that an object at one point will form an image at the other are called **conjugate foci** of the lens. We shall also learn that an important relation exists between the distance of the object from the lens (D_o), the distance of the image from the lens (D_i), and the focal length of the lens (f).

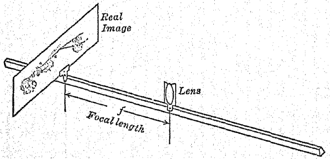


Fig. 123. Image of a distant object.

Directions. I. *Focal length.* Set the double convex lens and the cardboard screen on a meter stick (Fig. 123) and hold

the stick in the back part of the room but pointing at some distant object out of the window. Having placed the lens on one of the main divisions of the meter stick, move the screen toward and away from the lens until the most distant bright object which can be seen through the window is sharply focused on the screen, *i.e.*, forms a clear picture. Read and record the positions of lens and screen. *Compute the focal length of the lens.*

Move the lens to a new position on the stick, and again make a new setting of the screen in the same way as before. After making a third trial, find the average of the three focal lengths and record this as the focal length of the lens. Record also the number of the lens used.

II. ***Relations of object and image.*** Set up the meter stick as shown in figure 124 so that the object (an illuminated wire netting) is away from the window. Place the cardboard screen

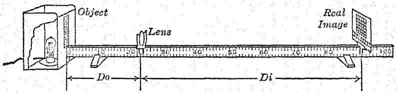


Fig. 124. Enlarged image of a near object.

at the opposite end and darken the room. Slide the lens back and forth between this screen and the object until a position is found where the picture of the netting appears on the screen as sharp as possible.

Is the image larger or smaller than the object?

Cover one part of the object and *see if the image is erect or inverted.*

Without moving the object or the screen, try to find another position of the lens that will give a sharp image. *Is it smaller or larger than the object, erect or inverted?*

When the image is smaller than the object, which is nearer the lens, the object or the image?

When the image is larger than the object, which is nearer the lens, the object or the image?

Record the position of the object and image and the two positions of the lens on the meter stick as accurately as possible, and arrange your data and results in tabular form as follows:

Positions			Object-Distance	Image-Distance	$\frac{1}{D_o}+\frac{1}{D_i}$	$\frac{1}{f}$
Object	Lens	Image				

Record the sum of the reciprocals of the object-distance $\left(\frac{1}{D_o}\right)$ and image-distance $\left(\frac{1}{D_i}\right)$ as a decimal fraction; also record the reciprocal of the focal length $\left(\frac{1}{f}\right)$ as a decimal to three significant figures. (Use Tables in Appendix.)

Move the screen up nearer the object and again find two positions where the lens forms a sharp image.

Continue to move the screen up closer to the object until it is possible to get only one distinct image. *What is the shortest distance between object and screen at which the lens will form a distinct image? How many times the focal length of the lens is this minimum distance between object and image?*

Compare the sum of the reciprocals of the image- and object-distances with the reciprocal of the focal length as determined in Part I.

Optional experiment. Make a careful study of a photographic camera. What sort of lens is used? Is it a fixed-focus, rectilinear, or anastigmatic lens? If it has a combination lens, remove the front lens and focus the camera on a printed page. Is the image formed everywhere sharp? Replace the front lens and again focus on a

printed page. What is the advantage of using a double lens? Why is the lens provided with a diaphragm having openings of various sizes, "stops"? How near can the camera be brought to an object and get a clear image? When does one want a "close-up"? Make a photograph with the camera and record all the data, such as the name of the camera, focal length of lens, stop used, time of exposure, date, time of day, quality of light, and name of plate or film used. Paste a print of the picture in your notebook.

QUESTIONS AND PROBLEMS

1. Explain why a small box camera requires no focusing.

2. If an arc lamp were placed at the principal focus of a convex lens, would the emerging rays be *divergent*, *parallel*, or *convergent?* Why?

3. At what distance would the object have to be in order that the image may be the same distance on the other side of the lens?

4. How many conjugate foci can your lens have?

5. The focal length of a double convex lens is 10 centimeters and the object is placed 30 centimeters from the lens. At what distance from the lens will the image be formed? Assume that $\frac{1}{D_o} + \frac{1}{D_i} = \frac{1}{f}$.

6. When an object is placed 10 centimeters from a double convex lens, its image is 40 centimeters on the other side. Find the focal length of the lens.

EXPERIMENT 61

SIZE AND SHAPE OF A REAL IMAGE

I. *Is the real image of a straight line formed by a convex lens straight or curved; and if curved, does its center bend toward or away from the lens?*

II. *How are the image-distance, object-distance, length of image, and length of object related?*

Strip of paper (about 20 × 75 cm.)	Block with vertical line
Meter stick	Hat pin
Double convex lens and holder	

Introduction. One important use of the double convex lens in optical instruments is to produce images which are larger

than the objects. The ratio of the diameter (or length) of the image to the diameter of the object is the **magnifying power** of the lens. In this experiment we shall see that there is an important relation between the diameters of the object and of the image and their respective distances from the lens.

Directions. Lay a strip of paper on the table so that the long side extends toward the window. Draw a line down the middle of the paper, and near the end farthest from the window draw an arrow about 10 centimeters long. Divide the arrow into four equal parts and mark the points of division 1, 2, 3, 4, and 5 as shown in figure 125. On the long line (the axis),

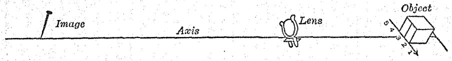


Fig. 125. Locating the image by parallax.

mark the position of the lens, which should be distant from point 3 of the arrow from one and a half to two times the focal length of the lens; that is, if the lens has a focal length of 12 centimeters, place it from 18 to 24 centimeters from the center of the arrow.

Place the lens so that its center is directly over this point and its plane at right angles to the line. To locate the image-points corresponding to each of the five points of the object, stand the vertical line of the wooden block directly over point 3, and using one eye only, look into the lens from the other end of the paper so as to see the image of the vertical line. Move the hat pin until it just covers the image. To see the pin and image distinctly, the eye should be about 25 centimeters away from the pin. Move the pin to and from the lens until a position is found where, as the head moves slowly from side to side, the pin and the image keep exactly together, showing that each is at the same distance from the eye. This is called the **parallax method.** As soon as this position is sharply determined, mark a dot directly under the point of the pin and label it 3′.

Move the vertical line along to 4 and locate in the same way the position of its image 4′. In this manner determine the position of the image of *each* of the five points of the object arrow. In locating these points it is very essential that the observer should not let any preconceived notion as to the proper position of the image-points affect his judgment as to where each image-point *really is*.

Construction. Connect the image-points 1′ and 2′, 2′ and 3′, etc., with straight lines to get a rough idea of the shape of the whole image. Draw a straight line from each object-point to its corresponding image-point. *Where do these lines intersect?*

Connect the ends of the image arrow by a straight line, measure its length, and call it L_i. Measure the distance of the lens from the center of the object and the distance of the lens from the point where the straight line (1′5′) joining the ends of the image crosses the axis, and call these distances D_o and D_i respectively.

Call the length of the object L_o. *Compute the value of the ratio* $\frac{L_i}{L_o}$, *which is called the magnifying power of the lens.* Also *compute the value of the ratio* $\frac{D_i}{D_o}$ *and compare this result with the magnifying power.* (Express the ratio as a decimal fraction to three significant figures.)

Does the center of the image bend toward the lens or away from it?

To explain this curvature of the image consider D_o for point 1 and D_o for point 3. Then, if the lens formula $\left(\frac{1}{D_o} + \frac{1}{D_i} = \frac{1}{f}\right)$ holds true, and f is a constant for the lens, what would be expected of D_i for point 1 and D_i for point 3?

How is this defect in a lens corrected so as to give what the photographers call a "flat image"?

Optional experiment. Study the size and shape of a virtual image in the way just described for the real image. In this case place the lens at or near the end of the median line and draw the object arrow

(about 5 centimeters long) at a distance from the lens equal to about two thirds its focal length. *How do you account for the shape of the virtual image? From your measurements what relation do you find between the distances of object and image from the lens and their lengths?*

QUESTIONS AND PROBLEMS

1. How can you distinguish between a real image and a virtual image?

2. Suppose a lighted candle were placed at point 3 of the object arrow and the room were darkened. Where would you place a cardboard screen to get a sharp image?

3. If a lens has a focal length of 36 centimeters, at what distance from the lens must an object be placed in order that the inverted image may be (*a*) half as long as the object; (*b*) twice as long?

4. An object 7.5 centimeters long is placed 50 centimeters from a lens; the image is 1.5 centimeters long. (*a*) What is the focal length of the lens? (*b*) Where is the image located?

EXPERIMENT 62

MAGNIFYING POWER OF A SIMPLE MICROSCOPE

How many diameters does a convex lens seem to magnify an object?

Meter stick	Paper millimeter scale
Double convex lens (f. 2.5–7.5 cm.) and holder	Cardboard with square hole and holder

Introduction. In many optical instruments a double convex lens is used as a simple microscope or magnifying glass. In such cases the distance between the lens and the object must be made a little *less* than the focal length and so adjusted that an erect enlarged virtual image is formed about 25 centimeters away, since this is generally assumed to be the distance of most distinct vision for the average person. To get the magnifying power of a simple microscope we have to find the ratio of the size of the image to the size of the object. This is, however, equal to the distance of the image divided by the distance of

the object, that is, $25/D_o$ where D_o is the object-distance in centimeters.

Directions. First find the focal length of the lens by holding a meter stick horizontally with one end against a piece of white cardboard and with the other end pointing at some distant object outside the window. Hold the lens in the hand and move it slowly away from the screen until it forms a clear picture, as in Experiment 60. This distance between the lens and the screen is the focal length of the lens. *Record the focal length and number of the lens.*

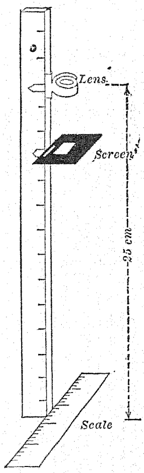


Fig. 126. How much does the lens magnify?

Place a paper millimeter scale on the table and stand a meter stick upright on it. At a distance of 25 centimeters fasten a short-focus lens to the meter stick. Then just under the lens set a cardboard screen with a square opening (1 cm.) at a distance a little less than the focal length of the lens, as shown in figure 126. Bring the head down so that the right eye is directly over the lens and adjust the screen so as to get a sharp image of its surface. Keeping both eyes open, count the number of millimeters which the image of the opening in the cardboard as seen by the right eye through the lens seems to correspond to on the millimeter scale as seen by the unaided left eye. *Divide this number by the width* (10 mm.) *of the opening in the cardboard; the quotient gives the number of times the object seems to be magnified when seen through the lens as compared with what it seems to be when seen with the naked eye at the distance of most distinct vision* (25 cm.).

Measure the distance of the opening in the cardboard from the center of the lens and call it D_o. Then since the distance

of the image is 25 centimeters, *the magnifying power of the lens can also be computed as the ratio* $25/D_o$.

Since the lens formula is $\frac{1}{D_o} + \frac{1}{D_i} = \frac{1}{f}$, and, for this virtual image, $D_i = -25$ cm., one gets the expression $\frac{1}{D_o} - \frac{1}{25} = \frac{1}{f}$, and the magnifying power is $\left(\frac{25}{D_o}\right) = 1 + \left(\frac{25}{f}\right)$. *Compute the magnifying power of the lens also by means of this equation, using the value of f found in the first part of this experiment. Record these three values of the magnifying power.*

Draw carefully a diagram to show the relative positions of the eyes, the lens, the opening in the cardboard, and the paper scale.

If time permits, repeat the experiment with another lens of slightly different focal length.

Optional experiment. Test your eyes for defects of vision. It is a very simple matter to make a few tests for **astigmatism** and for **acuteness of vision** for distant objects and for near objects. Get a test chart for vision (Allport's) and follow the printed directions. If you have any reason to think that your eyes need special attention, consult a competent oculist.

QUESTIONS AND PROBLEMS

1. Is it true that *everyone* sees an object most distinctly when the object is 25 centimeters (10 inches) from the eyes? Try it.

2. What are some of the practical uses of a simple microscope?

3. An object placed 5 centimeters from a convex lens has its image formed 15 centimeters from the lens on the same side. (*a*) What is the nature of the image (real or virtual)? (*b*) What is the focal length of the lens?

4. An object placed 5 centimeters from a lens has its image erect and magnified three diameters. (*a*) What is the image-distance? (*b*) What is the focal length of the lens?

EXPERIMENT 63

COMPOUND MICROSCOPE AND TELESCOPE

I. *How may two convex lenses be arranged to act like a compound microscope?*

II. *How may two convex lenses be arranged to act like a telescope?*

Two short-focus lenses (f. 2.5–7.5 cm.)	Cardboard screen and holder
	Two lens-holders
Long-focus lens (f. 25 cm.)	Screen with wire netting and holder
Meter stick and supports	

Electric or gas lamp

Introduction. The great advances made in modern medicine are due more largely to the use of the compound microscope than to any other instrument. In recent years its use has been greatly extended, so that now the scientist studies even rocks and metals with the aid of the compound microscope.

Ever since the days when Galileo made his first telescope to study the stars, the astronomer has used larger and larger telescopes. But we all use a form of telescope every time we look through a field glass or an opera glass. The civil engineer uses a type of telescope in his transit and level. The big guns of both the army and the navy are equipped with telescopic sights.

In this experiment we shall see that both the compound microscope and the telescope consist essentially of two convex lenses mounted at either end of a suitable tube. The lens near the eye is called the **eye-piece**, and the other lens is the **objective**. The objective forms a real image and the eye-piece serves as a simple microscope to magnify this real image.

Directions. I. ***Compound microscope.*** Measure the focal length of each of two short-focus lenses, as in Experiment 60. Mount one of the lenses O on a meter stick with the lamp and its wire netting AB at one end as shown in figure 127. Set up the cardboard screen S on the opposite side of the lens and

move the lens back and forth until a distinct and enlarged image of the illuminated netting is seen on the cardboard. Mount the other lens L on the other side of the cardboard S at such a distance that the surface of the card is seen distinctly when the eye is held close to the lens. Measure and record on a diagram the distances between the screen and lenses. Now remove the cardboard (leaving its holder) and look through the lens L, holding the eye close up to the lens. If necessary, move the eye-piece lens back and forth slightly until you see clearly the inverted image of the illuminated netting. In this

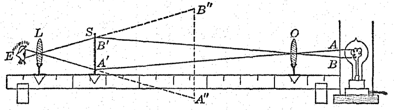


Fig. 127. Model to illustrate compound microscope.

set-up the lens L is used as a simple microscope to look at the real image formed by the objective lens at S. This combination of lenses represents a **compound microscope.**

Record the distance of the lamp netting from the objective lens. Compute the magnifying power of the objective from the ratio of the image-distance OS to the object-distance OA; then compute the magnifying power of the eye-piece as in the previous experiment; finally *compute the magnifying power of the compound microscope by multiplying the magnifying power of the objective by the magnifying power of the eye-piece.*

II. ***Astronomical telescope.*** Find the focal length of the long-focus lens, as in Experiment 60. Mount it on the meter stick where the objective lens was located in the demonstration microscope. Then move this long-focus objective lens back and forth along the meter stick until a sharp image of some distant object (such as the illuminated lamp box across the room) is formed on the cardboard screen placed at S. On the other side of the screen mount a short-focus lens (eye-piece) at

such a distance that the surface of the screen is seen distinctly when the eye is held close to the lens. Measure and record on a diagram the distance of the screen from each lens. Remove the cardboard and readjust the eye-piece, if necessary, so that when you look through the eye-piece you see distinctly an enlarged, inverted image of the distant object. These two lenses thus arranged constitute the essential parts of a very crude astronomical telescope. Measure the distance between the lenses and compare this distance with the sum of the focal lengths.

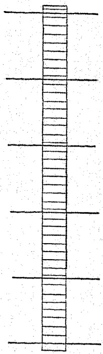


Fig. 128. Object and image.

To measure the magnifying power of the telescope, fasten on the opposite wall of the room a strip of white paper with a series of thick black lines drawn across it at regular intervals of about one inch. Be sure that this paper scale is about on a level with the axis of the telescope and that the lenses are so adjusted as to give a sharp image. Then look through the telescope with one eye and at the same time look at the scale directly with the other eye. Adjust the telescope so that object and image appear about as shown in figure 128, and so that one mark of the image exactly coincides with one mark of the object. Count the number of spaces between two successive marks of the image. *This gives the magnifying power of the telescope. Compare this value with the ratio of the focal length of the objective to the focal length of the eye-piece.*

Optional experiment. With a long-focus (40 cm.) double convex lens as an objective and with a concave lens as an eye-piece, set up a demonstration model of the **opera glass**, or Galilean telescope. Make the distance between the eye-piece and objective equal to the difference between the focal lengths of the two lenses.* Use a cardboard dia-

* To measure the focal length of a concave lens, allow the sunlight to fall upon the lens over which is a diaphragm. Receive the emergent light

phragm with a quarter-inch aperture mounted between the lenses near the eye-piece. *Is the image erect or inverted? How much is it magnified?* Measure the magnifying power of the model opera glass and compare the result with the ratio of the focal lengths of the objective and eye-piece.

QUESTIONS

1. Why is the focal length of the objective lens of a compound microscope always very short?

2. Why is the focal length of the objective of an astronomical telescope very long?

3. Why must the distance of the object from the objective in a compound microscope be adjusted with such great precision?

4. How would the magnifying power of a compound microscope be affected by lengthening the tube?

5. What are some of the defects in the models of compound microscope and astronomical telescope as just set up?

EXPERIMENT 64

SPECTRUM ANALYSIS *

How can a prism be used to study the light emitted or absorbed by various substances?

(For two students working together)

Glass prism (60° triangular)
Bunsen burner
Sheet-metal screen (30 × 30 cm.) with slit (0.3 × 15 cm.)
Asbestos- and blotting-paper strips (1 × 10 cm.)
Small samples of sodium chloride (table salt), sodium nitrate, lithium chloride, and thallium sulfate
Small pieces of red and blue glass
Knitting needle (polished steel)
4 Test tubes

Introduction. When sunlight passes through a prism, it is refracted on entering the glass and on emerging from it; but it

upon a screen at such a distance that the illuminated spot has twice the dimensions of the aperture in the diaphragm. Then the distance between the lens and the screen is the required focal length. Why?

* This experiment is based on a similar experiment in Crew and Tatnall's *Laboratory Manual of Physics.*

is also dispersed into all the colors of the rainbow, forming a colored band called a **spectrum.** It was in this way that Newton analyzed white light (sunlight) into its primary colors.

In this experiment we shall see how this principle of dispersion of light by a prism may be used to analyze substances into their elements. Under certain conditions we shall obtain a **continuous spectrum**, in which all the primary colors are present; under other conditions a **bright-line spectrum**, in which only certain bands of color are present, characteristic of the element; and under still other conditions an **absorption spectrum**, in which we have only certain colors left after some have been cut out. This whole subject of **spectrum analysis** is of great importance to the scientist not only in studying the composition of substances found on the earth but also in investigating the structure of the sun and the stars.

Directions. (a) ***Glowing carbon.*** Light one end of a strip of blotting paper and at once blow out the flame. The glowing end of the paper is red-hot carbon.* Hold a glass prism with its refracting angle vertical close to your eye and have your co-worker hold the blotter 1 to 3 meters away. Have him keep the tip of it glowing by blowing gently over it, while you look at it through the prism. *Compare the width of the image with that of the object. What colors do you observe through the prism? Which color is nearest the refracting angle of the prism? which farthest?*

(b) ***Gas flame.*** Place the slit of the sheet-metal screen in front of a luminous Bunsen flame (air-holes closed). Hold the refracting angle of the prism parallel to the slit, as shown in figure 129. *Compare the band of colors with that of glowing carbon (a). Are there any colors which are missing from the band of colors of the gas flame? What element is probably present in the flame?*

* The hot filament of an old-type incandescent lamp serves very well to show the colors of glowing carbon.

(c) ***Bunsen flame.*** Now open the air-holes in the Bunsen burner and examine with the prism the non-luminous flame. *What are the brightest colors present? Which colors are missing?*

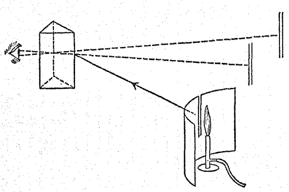


Fig. 129. How to see a bright-line spectrum.

(d) ***Sodium.*** Have your co-worker prepare in a test tube a solution of table salt (NaCl) and moisten thoroughly a strip of asbestos paper with it. Examine with the prism the Bunsen flame while your co-worker holds the tip of this moistened paper in the bottom of the flame. *What color predominates over all the others?* Label the strip.

In the same way moisten a small strip of asbestos paper with a solution of sodium nitrate ($NaNO_3$). Label the strip. *What color predominates strongly when this strip is touched to the flame? What element is found in both substances? Which color is produced by both?*

Observe the Bunsen flame with a prism while your co-worker lifts the burner a few centimeters and sets it down again quickly so as to jar some dust into the flame. *What color flashes out for an instant? What element is therefore in the dust?*

(e) ***Lithium.*** Have your co-worker moisten well a strip of asbestos paper with a dilute solution of lithium chloride (LiCl) and hold the tip of the paper in the bottom of the flame. *What color predominates?* Label the strip to prevent confusion.

(f) ***Thallium.*** Repeat the experiment with thallium sulfate (Tl_2SO_4). A bit, the size of a pinhead, dissolved in 2 or 3 cubic centimeters of water will supply enough material for this experiment. *What color, besides the ever-present yellow, predominates?* Label the strip of paper.

(g) ***Analysis.*** Now that you have examined the incandescent

vapor of the three elements, sodium, lithium, and thallium, let your co-worker place in the flame any one, two, three, or all four strips of paper without your knowledge of which or how many he holds. *Then see if you can tell which substance he is using.* This method of detecting elements is called **spectrum analysis.**

(h) ***Absorption.*** Have your co-worker make the flame luminous and hold a piece of red glass in front of the slit in the screen. *What are the principal colors which are thus cut out of the ordinary spectrum?* Repeat the experiment with blue glass. *What colors are cut out?* Place both red and blue glasses overlapping in front of the slit. *What colors pass through both glasses?* Such a spectrum is called an **absorption spectrum.**

(i) ***Solar spectrum.*** If the sun is shining, place two strips of wood on the window sill and across these a lead pencil and a polished knitting needle *KN* in the bright sunshine, as shown in figure 130. Standing at least 120 centimeters away, hold the edge of the prism parallel to the needle and observe it through the prism. You will find the spectrum crossed by several fine dark lines. *How many of these lines can you observe and in what colors do they lie?* These lines are called the **Fraunhofer lines.**

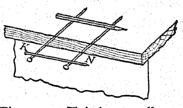


Fig. 130. **Knitting needle as mirror.**

Optional experiment. A **spectroscope** is an instrument equipped with one or more prisms, a slit, and a telescope for studying spectra. If such an instrument (preferably the direct-vision type) is available, examine with it the various spectra just described. *Show graphically the position of the bands of color.*

QUESTIONS

1. Of what colors is the sunlight composed?

2. Have the different colored lights the same index of refraction?

3. Why is the photographic plate a more sensitive means of examining spectra than the human eye?

RADIO

EXPERIMENT 65

ELECTRON TUBES *

What are the characteristics of a three-electrode vacuum tube?

- Radio receiving tube (such as U V-200) and socket
- Filament rheostat (10 ohms)
- Ammeter for filament
- Milliammeter for plate circuit (0–5) such as Weston 301
- Grid battery C (12-volt storage)
- Plate battery B (45 volts, dry cells)
- Filament battery A (6-volt storage)
- Voltmeter (0–30 volts)
- Rheostat to be used as a potentiometer
- Two-pole double-throw switch

Introduction. The electron tube is a recent invention which has made possible many important advances in radio communication. This tube not only serves as a detector of radio oscillations but is also used to generate, to amplify, and to modulate these same oscillations. It has found many applications in other fields of electrical engineering, such as in ordinary telephony with wires, where its use has made possible conversations over great distances (3000 miles).

The form of the tube is being rapidly improved. But the operation of this tube of whatever form and for whatever use depends on the properties of very minute particles of negative electricity, called **electrons**. A common form of detector tube

* For a more extended description of electron tubes and their uses, consult *Radio Communication Pamphlet No. 40*, prepared by U. S. Bureau of Standards. This book may be procured from Superintendent of Documents, Government Printing Office, Washington, D. C.

contains, besides the **filament**, a **plate** and a **grid** (Fig. 131). For this reason it is called a *three-electrode* vacuum tube. The incandescent filament shoots off electrons at a high velocity, each carrying its charge of negative electricity. If the plate is positively charged, there is a passing of electrons to the plate which is equivalent to the flow of current *from* the plate *to* the filament, according to the usual idea of the flow of an electric current from the positive to the negative potential. Please note this distinction between the direction of *electron flow* and *current flow*. Nevertheless remember that the magnitude of the current flowing through the tube from the plate is determined by the number of electrons that travel across the tube and reach the plate per second.

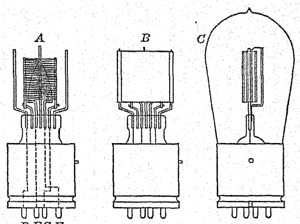


Fig. 131. Electron tube: *A*, Filament with grid around it; *B*, plate mounted; *C*, Side view of complete tube.

If we increase the filament current, we thereby increase the filament temperature, which means that more electrons are shot off. If we increase the plate voltage, we also increase the number of electrons reaching the plate every second, which means that we increase the plate current.

By introducing the **grid** between the filament and the plate, we have another most effective means of controlling the plate current. By making the potential of the grid *positive* or *negative* as regards the filament, it is possible to hasten or obstruct the flow of electrons and thus to vary the plate current.

In this experiment we shall study the relation between the *grid potential* and the *plate current*. As a result of our measurements we shall be able to plot a characteristic curve to show

graphically this relationship, because it is upon such a curve that the most commonly accepted explanation of the tube's operation is based. This is only one of several characteristic curves which are used to study the relationship between the several factors — plate potential, plate current, grid potential, grid current, and filament current. Two variable factors having been selected, the other three must remain fixed.

Directions. ***Connections.*** The apparatus should be connected up as shown in figure 132. It will be seen that besides the "A" battery in the filament circuit and the "B" battery in the plate circuit, we have a third battery in the grid circuit. It will also be noted that there is a rheostat placed across the

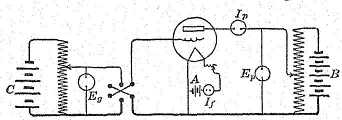


Fig. 132. Measuring plate current with various grid potentials.

grid battery C to serve as a potentiometer so that we may quickly get positive and negative grid potentials. The milliammeter (Ip) in the plate circuit measures the *plate current*, and the voltmeter (Eg) measures the *grid voltage*. The filament current as recorded by the filament ammeter is kept constant, and the plate voltage as recorded by the voltmeter across the terminals of the "B" battery is also kept constant.

First adjust the filament rheostat until the filament current as indicated by the ammeter I_f is normal; that is, whatever is specified by the makers of the tube as normal. Then set the plate voltage at 40 volts. Now measure the plate current for several potentials of the grid referred to the filament, such as -6, -4, -2, 0, $+2$, $+4$, and $+6$ volts. It will be found convenient to insert a two-pole double-throw switch in the grid circuit in order to change quickly from positive to negative potentials.

Results. Plot on coördinate paper the grid voltages horizontally and the plate current (in milliamperes) vertically.

If time permits, repeat the experiment using 20 volts as the plate voltage, and again using 60 volts.

This characteristic curve will well repay careful study. If the plate current increases directly as the grid voltage, then the curve will be a straight line. *Is your curve or any part of it approximately a straight line? What does it mean?* If the plate current increases more rapidly over a certain range than over another (for a given change in grid potential), then the curve will be steeper over that range. *What part of your curve is steepest? What does this indicate?* If the tube reaches a saturation point where an increase in grid potential produces almost no increase in the plate current, the curve will flatten out into a horizontal line at the upper extremity. *Have you reached the saturation point?*

In using such a tube as a detector, it is desirable to arrange the conditions so that a small change in grid voltage will produce the maximum change in plate current. *What grid potential would you suggest as desirable for your tube? Why?*

Optional experiment. An important factor about an electron tube is the **amplification coefficient.** For example, in the average detector tube increasing the potential of the grid one volt will produce as much increase in plate current as will be brought about by increasing the plate voltage by 5 to 10 volts. This may be roughly determined by adding another potentiometer to the apparatus shown in figure 132 across the "*B*" battery so that we can vary the plate voltage. Adjust the two potentiometers so that the plate voltage is 40 volts and the grid voltage is 0 volts; then measure the plate current. Now increase the grid voltage by 0.2 volts and decrease the plate voltage until the plate current is the same as before. Suppose the new setting gives a plate voltage of 38 volts. Then the amplification coefficient of the tube is the change of plate voltage (2 volts) divided by the change of grid voltage (0.2) (plate current remaining constant), or 10.

Make several determinations of the amplification coefficient at various points on the characteristic curve.

QUESTIONS

1. If the plate current increased directly as the plate voltage, what law would this illustrate?

2. If you increase the filament current, you also increase very rapidly the plate current up to a certain saturation point. How do you explain this on the theory of electrons?

3. In a receiving set using a detector tube, (*a*) what takes the place of the grid battery? (*b*) what takes the place of the plate-circuit ammeter?

4. How does the grid current compare with the plate current?

5. If an alternating e. m. f. is impressed on the grid, what happens in the plate circuit?

Relative humidity = $\dfrac{\text{amount of moisture present}}{\text{amt. of moisture required to saturate}}$

APPENDIX

I. Rules for Computation

$$\text{Area of triangle} = \frac{\text{base} \times \text{altitude}}{2}$$

$$\text{Circumference of circle} = \pi D$$

$$\text{Area of circle} = \pi R^2$$

$$\text{Surface of sphere} = 4\,\pi R^2$$

$$\text{Volume of sphere} = \frac{4\,\pi R^3}{3}$$

$$\left.\begin{array}{l}\text{Volume of prism}\\ \text{Volume of cylinder}\end{array}\right\} = \text{area of base} \times \text{altitude}$$

$$\pi = 3\tfrac{1}{7}, \text{ or } 3.14$$

II. Table of Equivalents

1 centimeter = 0.394 inch	1 inch = 2.54 centimeters
1 kilometer = 0.621 mile	1 foot = 30.5 centimeters
1 kilogram = 2.20 pounds	1 ounce = 28.4 grams
1 liter = 1.06 quarts	1 pound = 454 grams
1 cm.^{3} water weighs 1 gram	1 cu. ft. water weighs 62.4 pounds

III. Table of Densities

(In grams per cubic centimeter)

Alcohol, 95 %	0.807	Lead	11.4
Aluminum	2.65	Marble	2.5–2.8
Brass	8.4–8.7	Mercury	13.6
Coal (anthracite)	1.4–1.8	Platinum	21.5
Copper	8.93	Silver	10.5
Gasoline	0.68–0.72	Tin	7.3
Glass (flint)	3.0–3.6	Sea Water	1.03
Glass (crown)	2.5–2.7	Wood — Ebony	1.2
Gold	19.3	Oak	0.7–0.9
Ice	0.911	Pine	0.4–0.6
Iron	7.1–7.9	Zinc	7.1

IV. Density of Dry Air at Different Temperatures and Pressures (Grams per Liter)

Temp.	Pressure in Millimeters							
	710	720	730	740	750	760	770	780
0° C.	1.208	1.225	1.242	1.259	1.276	1.293	1.310	1.327
2	1.199	1.216	1.233	1.250	1.267	1.284	1.300	1.317
4	1.190	1.207	1.224	1.241	1.258	1.274	1.291	1.308
6	1.182	1.199	1.215	1.232	1.248	1.265	1.282	1.298
8	1.173	1.190	1.207	1.223	1.240	1.256	1.273	1.289
10	1.165	1.182	1.198	1.214	1.231	1.247	1.264	1.280
12	1.157	1.173	1.190	1.206	1.222	1.238	1.255	1.271
14	1.149	1.165	1.181	1.197	1.214	1.230	1.246	1.262
16	1.141	1.157	1.173	1.189	1.205	1.221	1.237	1.253
18	1.133	1.149	1.165	1.181	1.197	1.213	1.229	1.245
20	1.125	1.141	1.157	1.173	1.189	1.205	1.220	1.236
22	1.118	1.133	1.149	1.165	1.181	1.196	1.212	1.228
24	1.110	1.126	1.141	1.157	1.173	1.188	1.204	1.220
26	1.103	1.118	1.134	1.149	1.165	1.180	1.196	1.211
28	1.095	1.111	1.126	1.142	1.157	1.173	1.188	1.203
30	1.088	1.103	1.119	1.134	1.149	1.165	1.180	1.195

V. Tensile Strength of Wire

Material	Pounds per Square Inch	Material	Pounds per Square Inch
Aluminum, rolled .	16,500–22,400	Lead	2,420–3,130
Brass wire . . .	40,800–77,900	Platinum . . .	26,310–31,720
Bronze, phosphor .	36,000–40,500	Steel	81,500–90,600
Copper, hard-drawn	49,000–67,000	Steel, crucible .	163,000–185,000
Iron, ordinary . .	40,800–65,100	Zinc	18,060

VI. Coefficients of Linear Expansion of Solids

Aluminum	0.0000231	"Invar" (Nickel steel)	0.0000009
Brass	0.0000189	Quartz (fused)	0.0000005
Copper	0.0000167	Steel	0.000011
Glass (soft)	0.0000085	Zinc	0.000026

VII. Specific Heats of Various Substances

Solids

Aluminum	0.219	Lead	0.0305
Brass	0.090	Nickel	0.109
Copper	0.0936	Platinum	0.0324
Glass	0.190	Silver	0.056
Ice	0.502	Tin	0.055
Iron	0.119	Zinc	0.093

Liquids

Alcohol, ethyl at 17° C.	0.602	Kerosene	0.5–0.6
Carbon disulphide at 15° C.	0.230	Mercury at 20° C.	0.0333
Glycerin, 0°–100° C.	5.076	Water	1.000

VIII. Weight of Water Vapor in Saturated Air

Temperature ° F.	Weight in Grains* per Cubic Foot	Temperature ° C.	Weight in Grams per Cubic Meter
− 20°	0.21	− 30°	0.44
0	0.54	− 20	1.04
+ 20	1.30	− 10	2.28
40	2.86	0	4.87
50	4.09	+ 10	9.36
60	5.76	20	17.15
70	7.99	30	30.08
80	10.95	+ 40	50.67

* One pound (Avoirdupois) is equal to 7000 grains.

IX. Relative Humidity, per Cent.

Dry-bulb Thermometer ° F.	Difference between Dry- and Wet-bulb Thermometers												
	5.0°	6.0°	7.0°	8.0°	9.0°	10.0°	11.0°	12.0°	13.0°	14.0°	15.0°	16.0°	17.0°
60°	73	68	63	58	53	48	44	39	34	30	26	22	18
61°	73	68	63	58	54	49	44	40	35	32	27	23	19
62°	74	69	64	59	54	50	45	41	37	32	28	24	20
63°	74	69	64	60	55	50	46	42	37	33	29	25	21
64°	74	70	65	60	56	51	47	43	38	34	30	26	22
65°	75	70	66	61	56	52	48	44	39	35	31	27	24
66°	75	71	66	61	57	53	48	44	40	36	32	29	25
67°	75	71	66	62	58	53	49	45	41	37	33	30	26
68°	76	71	67	62	58	54	50	46	42	38	34	31	27
69°	76	72	67	63	59	55	51	47	43	39	35	32	28
70°	77	72	68	64	59	55	51	48	44	40	36	33	29
71°	77	72	68	64	60	56	52	48	45	41	37	33	30
72°	77	73	69	65	61	57	53	49	45	42	38	34	31
73°	78	73	69	65	61	57	53	50	46	42	39	35	32
74°	78	74	70	66	62	58	54	50	47	43	40	36	33

This table is calculated for rapid forced ventilation.

X. Resistance of Annealed Copper Wire

B. & S. Gauge	Diameter in Millimeters	Diameter in Mils	Area in Circular Mils	Ohms per 1000 Ft. at 20° C.	Feet per Lb., Double Cotton Covered
10	2.59	101.9	10,380.	1.00	30.9
11	2.31	90.7	8,234.	1.26	38.9
12	2.05	80.8	6,530.	1.59	48.8
13	1.83	72.0	5,178.	2.00	61.5
14	1.63	64.1	4,107.	2.52	77.4
15	1.45	57.1	3,257.	3.18	97.2
16	1.29	50.8	2,583.	4.01	122.
17	1.15	45.3	2,048.	5.06	153.
18	1.02	40.3	1,624.	6.37	192.
19	.90	35.4	1,288.	8.04	247.
20	.81	32.0	1,022.	10.1	298.
21	.72	28.5	810.	12.8	375.
22	.64	25.3	643.	16.1	472.
23	.57	22.6	509.	20.3	585.
24	.51	20.1	404.	25.6	730.
25	.46	17.90	320.	32.3	901.
26	.41	15.94	254.	40.8	1123.
27	.36	14.20	202.	51.4	1389.
28	.32	12.64	159.8	64.8	1695.
29	.29	11.26	126.7	81.7	2127.
30	.26	10.02	100.5	103.	2564.
31	.23	8.93	79.7	130.	
32	.20	7.95	63.2	164.	
33	.18	7.08	50.1	207.	
34	.16	6.30	39.7	261.	
35	.14	5.61	31.5	328.	
36	.13	5.00	25.0	414.	

It will be noticed in the table above that #13 wire is about half the size of #10 wire, and so has twice as much resistance. In the same way #16 wire is half the size of #13, and has double the resistance.

SINE AND TANGENT OF AN ANGLE

Let BAC (Fig. 133) be any given angle. From *any* point B on one side of the angle draw a perpendicular BC to the other side, thus forming the right-angled triangle ABC. Suppose we measure the hypotenuse AB and find it to be 10.00 centimeters and the opposite side BC and find it to be 5.05 centimeters. Then the ratio of the opposite side to the hypotenuse is $\frac{BC}{AB} = \frac{5.05}{10.00} = 0.505$. We might choose any other point on AB but in any case we should obtain the same value for the ratio of the *opposite side* to the *hypotenuse* so long as we used the same angle BAC.

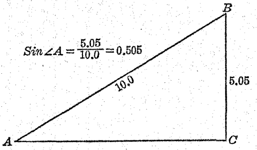


Fig. 133. Sine of an angle.

In the same way we might measure the *opposite side* BC and the *adjacent side* AC. We should find that the ratio of the opposite side to the adjacent side $\frac{BC}{AC}$ is constant for any given angle.

In mathematics these constant ratios have been given distinguishing names.

The ratio $\frac{BC}{AB}$ is called the ***sine*** of the angle BAC.

The ratio $\frac{BC}{AC}$ is called the ***tangent*** of the angle BAC.

The values of these ratios have been calculated for all angles and are given in trigonometric tables. These ratios, with the values carried out to three decimals, will be found on page 239. They are called the ***natural sines*** and ***natural tangents*** to distinguish them from the logarithmic sines and tangents.

It will be helpful to remember that the tangent of an angle of 45° is 1 since in this case BC is equal to AC. For angles less than 45°, the tangent is less than 1 and for angles between 45° and 90° it is more than 1, being infinity at 90°. It is also obvious that no angle can have a sine greater than 1.

XI. Natural Sines and Tangents

Angle	Sine	Tangent	Angle	Sine	Tangent	Angle	Sine	Tangent
0°	*0.000*	0.000	**31°**	*0.515*	0.601	**62°**	*0.883*	1.881
1	*0.017*	0.017	**32**	*0.530*	0.625	**63**	*0.891*	1.963
2	*0.035*	0.035	**33**	*0.545*	0.649	**64**	*0.899*	2.050
3	*0.052*	0.052	**34**	*0.559*	0.675	**65**	*0.906*	2.145
4	*0.070*	0.070	**35**	*0.574*	0.700	**66**	*0.914*	2.246
5	*0.087*	0.087	**36**	*0.588*	0.727	**67**	*0.921*	2.356
6	*0.105*	0.105	**37**	*0.602*	0.754	**68**	*0.927*	2.475
7	*0.122*	0.123	**38**	*0.616*	0.781	**69**	*0.934*	2.605
8	*0.139*	0.141	**39**	*0.629*	0.810	**70**	*0.940*	2.747
9	*0.156*	0.158	**40**	*0.643*	0.839	**71**	*0.946*	2.904
10	*0.174*	0.176	**41**	*0.656*	0.869	**72**	*0.951*	3.078
11	*0.191*	0.194	**42**	*0.669*	0.900	**73**	*0.956*	3.271
12	*0.208*	0.213	**43**	*0.682*	0.933	**74**	*0.961*	3.487
13	*0.225*	0.231	**44**	*0.695*	0.966	**75**	*0.966*	3.732
14	*0.242*	0.249	**45**	*0.707*	1.000	**76**	*0.970*	4.011
15	*0.259*	0.268	**46**	*0.719*	1.036	**77**	*0.974*	4.331
16	*0.276*	0.287	**47**	*0.731*	1.072	**78**	*0.978*	4.705
17	*0.292*	0.306	**48**	*0.743*	1.111	**79**	*0.982*	5.145
18	*0.309*	0.325	**49**	*0.755*	1.150	**80**	*0.985*	5.671
19	*0.326*	0.344	**50**	*0.766*	1.192	**81**	*0.988*	6.314
20	*0.342*	0.364	**51**	*0.777*	1.235	**82**	*0.990*	7.115
21	*0.358*	0.384	**52**	*0.788*	1.280	**83**	*0.993*	8.144
22	*0.375*	0.404	**53**	*0.799*	1.327	**84**	*0.995*	9.514
23	*0.391*	0.424	**54**	*0.809*	1.376	**85**	*0.996*	11.43
24	*0.407*	0.445	**55**	*0.819*	1.428	**86**	*0.998*	14.30
25	*0.423*	0.466	**56**	*0.829*	1.483	**87**	*0.999*	19.08
26	*0.438*	0.488	**57**	*0.839*	1.540	**88**	*0.999*	28.64
27	*0.454*	0.510	**58**	*0.848*	1.600	**89**	*1.000*	57.29
28	*0.469*	0.532	**59**	*0.857*	1.664	**90**	*1.000*	Infinity
29	*0.485*	0.554	**60**	*0.866*	1.732			
30	*0.500*	0.577	**61**	*0.875*	1.804			

HINTS ABOUT PLOTTING CURVES

We are probably already familiar with graphs as used to represent algebraic equations. We have all seen curves in the newspapers to show the changes in the population of a city or the price of sugar during a series of years. Here we are plotting population versus time or prices versus time. In scientific work we frequently have a result which changes according to some variable factor and we wish to show graphically just how the result depends upon this factor.

For example, suppose we find that a certain liquid cools as shown by the following data:

Time	2 min.	6	8	13	18	24	32	38	44	49
Temp.	73° C.	64	58	51	45	38	32	27	23	21

On a sheet of coördinate paper which is ruled in squares, we select a certain horizontal line near the bottom as the *time* axis and a certain vertical line to the left as the *temperature* axis; the intersection of the two lines (in the lower left-hand corner) is called the *origin*. In this case we shall find it convenient to let each horizontal space represent 5 minutes and each vertical space 10°. Each observation given in our table is then plotted as shown in figure 134. The origin represents the beginning of the experiment, 2 minutes is represented by $\frac{2}{5}$ of the first space to the right, and 73° is $\frac{3}{10}$ of a space above the 70° line and directly over the proper time space. At this point we make a dot and then make it conspicuous by drawing through it fine cross-lines, or, better still, by drawing a tiny circle around the point. In the same way the other points are plotted and a curve is drawn through the resulting points. It will be noted that it was not possible to draw a smooth curve through all the points, so we assume that those points not exactly on the curve are probably somewhat in error.

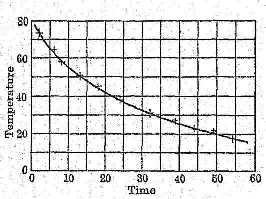


Fig. 134. Cooling curve of a liquid.

It requires some experience to choose the proper scale for two sets of variables, but it is evident that the two scales need not be alike. It is

desirable to choose such a scale that the points cover a large part of the sheet of paper in both directions. Often it is more convenient to have the origin not represent the zero value on each scale but some round number just under the minimum value. The quantity represented by each scale must be plainly indicated and also the units used.

SUGGESTED TIME SCHEDULE

Chapter	Subject	Time	Experiments
I	Introduction: Weights and Measures	1 week	1 and 2
II	Simple Machines	5 weeks	3 to 9
III	Mechanics of Liquids	3 weeks	10 to 13
IV	Mechanics of Gases	2 weeks	14 to 17
V	Non-parallel Forces	1 week	18 to 20
VI	Elasticity and Strength of Materials	1 week	21 to 23
VII	Accelerated Motion	1 week	24
VIII	Three Laws of Motion	1 week	25
IX	Potential and Kinetic Energy	1 week	26
X	Heat-expansion and Transmission	3 weeks	27 to 30
XI	Water, Ice, and Steam	2 weeks	31 to 35
XII	Heat Engines	1 week	36
XIII	Magnetism	½ week	37
XIV	Static Electricity	½ week	
XV	Electric Currents	2 weeks	38 to 42
XVI	Effects of an Electric Current	2 weeks	43 to 46
XVII	Induced Currents	2 weeks	47 to 49
XVIII	Alternating Currents	1 week	50 to 52
XIX	Sound	2 weeks	53 to 55
XX	Illumination: Lamps and Reflectors	2 weeks	56 to 58
XXI	Lenses and Optical Instruments	2 weeks	59 to 63
XXII	Spectra and Color	1 week	64
XXIII	Electric Waves: X-Rays and Radio-activity	1 week	65
	Total	38 weeks	

N	0	1	2	3	4	5	6	7	8	9	Subtract Differences 1	2	3	4	5	6	7	8	9
10	1000	9901	9804	9709	9615	9524	9434	9346	9259	9174	9	18	27	36	45	55	64	73	82
11	9091	9009	8929	8850	8772	8696	8621	8547	8475	8403	8	15	23	30	38	45	53	61	68
12	8333	8264	8197	8130	8065	8000	7937	7874	7813	7752	6	13	19	26	32	38	45	51	58
13	7692	7634	7576	7519	7463	7407	7353	7299	7246	7194	5	11	16	22	27	33	38	44	49
14	7143	7092	7042	6993	6944	6897	6849	6803	6757	6711	5	10	14	19	24	29	33	38	43
15	6667	6623	6579	6536	6494	6452	6410	6369	6329	6289	4	8	13	17	21	25	29	33	38
16	6250	6211	6173	6135	6098	6061	6024	5988	5952	5917	4	7	11	15	18	22	26	29	33
17	5882	5848	5814	5780	5747	5714	5682	5650	5618	5587	3	6	10	13	16	20	23	26	29
18	5556	5525	5495	5464	5435	5405	5376	5348	5319	5291	3	6	9	12	15	17	20	23	26
19	5263	5236	5208	5181	5155	5128	5102	5076	5051	5025	3	5	8	11	13	16	18	21	24
20	5000	4975	4950	4926	4902	4878	4854	4831	4808	4785	2	5	7	10	12	14	17	19	21
21	4762	4739	4717	4695	4673	4651	4630	4608	4587	4566	2	4	7	9	11	13	15	17	19
22	4545	4525	4505	4484	4464	4444	4425	4405	4386	4367	2	4	6	8	10	12	14	16	18
23	4348	4329	4310	4292	4274	4255	4237	4219	4202	4184	2	4	5	7	9	11	13	14	16
24	4167	4149	4132	4115	4098	4082	4065	4049	4032	4016	2	3	5	7	8	10	12	13	15
25	4000	3984	3968	3953	3937	3922	3906	3891	3876	3861	2	3	5	6	8	9	11	12	14
26	3846	3831	3817	3802	3788	3774	3759	3745	3731	3717	1	3	4	6	7	8	10	11	13
27	3704	3690	3676	3663	3650	3636	3623	3610	3597	3584	1	3	4	5	7	8	9	11	12
28	3571	3559	3546	3534	3521	3509	3497	3484	3472	3460	1	2	4	5	6	7	9	10	11
29	3448	3436	3425	3413	3401	3390	3378	3367	3356	3344	1	2	3	5	6	7	8	9	10
30	3333	3322	3311	3300	3289	3279	3268	3257	3247	3236	1	2	3	4	5	6	7	9	10
31	3226	3215	3205	3195	3185	3175	3165	3155	3145	3135	1	2	3	4	5	6	7	8	9
32	3125	3115	3106	3096	3086	3077	3067	3058	3049	3040	1	2	3	4	5	6	7	8	9
33	3030	3021	3012	3003	2994	2985	2976	2967	2959	2950	1	2	3	4	4	5	6	7	8
34	2941	2933	2924	2915	2907	2899	2890	2882	2874	2865	1	2	3	3	4	5	6	7	8
35	2857	2849	2841	2833	2825	2817	2809	2801	2793	2786	1	2	2	3	4	5	6	6	7
36	2778	2770	2762	2755	2747	2740	2732	2725	2717	2710	1	2	2	3	4	5	5	6	7
37	2703	2695	2688	2681	2674	2667	2660	2653	2646	2639	1	1	2	3	4	4	5	6	6
38	2632	2625	2618	2611	2604	2597	2591	2584	2577	2571	1	1	2	3	3	4	5	5	6
39	2564	2558	2551	2545	2538	2532	2525	2519	2513	2506	1	1	2	3	3	4	4	5	6
40	2500	2494	2488	2481	2475	2469	2463	2457	2451	2445	1	1	2	2	3	4	4	5	5
41	2439	2433	2427	2421	2415	2410	2404	2398	2392	2387	1	1	2	2	3	3	4	5	5
42	2381	2375	2370	2364	2358	2353	2347	2342	2336	2331	1	1	2	2	3	3	4	4	5
43	2326	2320	2315	2309	2304	2299	2294	2288	2283	2278	1	1	2	2	3	3	4	4	5
44	2273	2268	2262	2257	2252	2247	2242	2237	2232	2227	1	1	2	2	3	3	4	4	5
45	2222	2217	2212	2208	2203	2198	2193	2188	2183	2179	0	1	1	2	2	3	3	4	4
46	2174	2169	2165	2160	2155	2151	2146	2141	2137	2132	0	1	1	2	2	3	3	4	4
47	2128	2123	2119	2114	2110	2105	2101	2096	2092	2088	0	1	1	2	2	3	3	4	4
48	2083	2079	2075	2070	2066	2062	2058	2053	2049	2045	0	1	1	2	2	3	3	3	4
49	2041	2037	2033	2028	2024	2020	2016	2012	2008	2004	0	1	1	2	2	2	3	3	4
50	2000	1996	1992	1988	1984	1980	1976	1972	1969	1965	0	1	1	2	2	2	3	3	4
51	1961	1957	1953	1949	1946	1942	1938	1934	1931	1927	0	1	1	2	2	2	3	3	3
52	1923	1919	1916	1912	1908	1905	1901	1898	1894	1890	0	1	1	1	2	2	3	3	3
53	1887	1883	1880	1876	1873	1869	1866	1862	1859	1855	0	1	1	1	2	2	2	3	3
54	1852	1848	1845	1842	1838	1835	1832	1828	1825	1821	0	1	1	1	2	2	2	3	3
	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
											Subtract Differences								

N	0	1	2	3	4	5	6	7	8	9	Subtract Differences								
											1	2	3	4	5	6	7	8	9
55	1818	1815	1812	1808	1805	1802	1799	1795	1792	1789	0	1	1	1	2	2	2	3	3
56	1786	1783	1779	1776	1773	1770	1767	1764	1761	1757	0	1	1	1	2	2	2	3	3
57	1754	1751	1748	1745	1742	1739	1736	1733	1730	1727	0	1	1	1	2	2	2	2	3
58	1724	1721	1718	1715	1712	1709	1706	1704	1701	1698	0	1	1	1	1	2	2	2	3
59	1695	1692	1689	1686	1684	1681	1678	1675	1672	1669	0	1	1	1	1	2	2	2	3
60	1667	1664	1661	1658	1656	1653	1650	1647	1645	1642	0	1	1	1	1	2	2	2	3
61	1639	1637	1634	1631	1629	1626	1623	1621	1618	1616	0	1	1	1	1	2	2	2	2
62	1613	1610	1608	1605	1603	1600	1597	1595	1592	1590	0	1	1	1	1	2	2	2	2
63	1587	1585	1582	1580	1577	1575	1572	1570	1567	1565	0	0	1	1	1	1	2	2	2
64	1563	1560	1558	1555	1553	1550	1548	1546	1543	1541	0	0	1	1	1	1	2	2	2
65	1538	1536	1534	1531	1529	1527	1524	1522	1520	1517	0	0	1	1	1	1	2	2	2
66	1515	1513	1511	1508	1506	1504	1502	1499	1497	1495	0	0	1	1	1	1	2	2	2
67	1493	1490	1488	1486	1484	1481	1479	1477	1475	1473	0	0	1	1	1	1	2	2	2
68	1471	1468	1466	1464	1462	1460	1458	1456	1453	1451	0	0	1	1	1	1	2	2	2
69	1449	1447	1445	1443	1441	1439	1437	1435	1433	1431	0	0	1	1	1	1	1	2	2
70	1429	1427	1425	1422	1420	1418	1416	1414	1412	1410	0	0	1	1	1	1	1	2	2
71	1408	1406	1404	1403	1401	1399	1397	1395	1393	1391	0	0	1	1	1	1	1	2	2
72	1389	1387	1385	1383	1381	1379	1377	1376	1374	1372	0	0	1	1	1	1	1	2	2
73	1370	1368	1366	1364	1362	1361	1359	1357	1355	1353	0	0	1	1	1	1	1	2	2
74	1351	1350	1348	1346	1344	1342	1340	1339	1337	1335	0	0	1	1	1	1	1	1	2
75	1333	1332	1330	1328	1326	1325	1323	1321	1319	1318	0	0	1	1	1	1	1	1	2
76	1316	1314	1312	1311	1309	1307	1305	1304	1302	1300	0	0	1	1	1	1	1	1	2
77	1299	1297	1295	1294	1292	1290	1289	1287	1285	1284	0	0	0	1	1	1	1	1	1
78	1282	1280	1279	1277	1276	1274	1272	1271	1269	1267	0	0	0	1	1	1	1	1	1
79	1266	1264	1263	1261	1259	1258	1256	1255	1253	1252	0	0	0	1	1	1	1	1	1
80	1250	1248	1247	1245	1244	1242	1241	1239	1238	1236	0	0	0	1	1	1	1	1	1
81	1235	1233	1232	1230	1229	1227	1225	1224	1222	1221	0	0	0	1	1	1	1	1	1
82	1220	1218	1217	1215	1214	1212	1211	1209	1208	1206	0	0	0	1	1	1	1	1	1
83	1205	1203	1202	1200	1199	1198	1196	1195	1193	1192	0	0	0	1	1	1	1	1	1
84	1190	1189	1188	1186	1185	1183	1182	1181	1179	1178	0	0	0	1	1	1	1	1	1
85	1176	1175	1174	1172	1171	1170	1168	1167	1166	1164	0	0	0	1	1	1	1	1	1
86	1163	1161	1160	1159	1157	1156	1155	1153	1152	1151	0	0	0	1	1	1	1	1	1
87	1149	1148	1147	1145	1144	1143	1142	1140	1139	1138	0	0	0	1	1	1	1	1	1
88	1136	1135	1134	1133	1131	1130	1129	1127	1126	1125	0	0	0	1	1	1	1	1	1
89	1124	1122	1121	1120	1119	1117	1116	1115	1114	1112	0	0	0	1	1	1	1	1	1
90	1111	1110	1109	1107	1106	1105	1104	1103	1101	1100	0	0	0	1	1	1	1	1	1
91	1099	1098	1096	1095	1094	1093	1092	1091	1089	1088	0	0	0	0	1	1	1	1	1
92	1087	1086	1085	1083	1082	1081	1080	1079	1078	1076	0	0	0	0	1	1	1	1	1
93	1075	1074	1073	1072	1071	1070	1068	1067	1066	1065	0	0	0	0	1	1	1	1	1
94	1064	1063	1062	1060	1059	1058	1057	1056	1055	1054	0	0	0	0	1	1	1	1	1
95	1053	1052	1050	1049	1048	1047	1046	1045	1044	1043	0	0	0	0	1	1	1	1	1
96	1042	1041	1040	1038	1037	1036	1035	1034	1033	1032	0	0	0	0	1	1	1	1	1
97	1031	1030	1029	1028	1027	1026	1025	1024	1022	1021	0	0	0	0	1	1	1	1	1
98	1020	1019	1018	1017	1016	1015	1014	1013	1012	1011	0	0	0	0	1	1	1	1	1
99	1010	1009	1008	1007	1006	1005	1004	1003	1002	1001	0	0	0	0	0	1	1	1	1
	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
											Subtract Differences								

S. C. Katyal

APPARATUS LIST

RECOMMENDED FOR THE TWENTY-FIVE STARRED EXPERIMENTS WHICH ARE REGARDED AS FUNDAMENTAL

Numbers in parentheses refer to experiments.

Rectangular wooden block (2, 11, 57)
Ruler, 30 cm. and 12 in. (2, 18, 57, 59)
Platform balance (Troemner model) with rider (2, 12, 31, 34)
(*Or,* Laboratory beam balance with rider)
Metric brass weights, 1 to 1000 grams, in block (2, 4, 6, 7, 12, 31, 34)
Meter stick, Eng. and metric graduations (4, 6, 7, 28, 29, 54, 60)
Rider weight (lead) to fit meter stick (4)
Triangular wooden block (4)
Smooth board with rails and pulley for inclined plane (6, 7)
Hall's car (6)
Spring balance, 2000 grams and 64 oz. (3 required) (6, 7, 18)
Friction box with runners (7)
Spring balance, 250 grams and 8 oz. (11)
Lead sinker with hook (11)
Battery jar, 6×8 in. (2 required) (11, 12)
Wide-mouthed glass-stoppered bottle, 50 $cm.^3$ (12)
Hydrometer for light liquids (12)
Hydrometer for heavy liquids (12)
Boyle's-law tube, J-form (16)
(*Or,* Adjustable Boyle's-law apparatus with stopcock, mounted on support)
Mercury, 1 lb. (16)
Mercurial barometer, Fortin cistern, with scale in in. and mm. (16, 28, 34)
Metric cross-section paper, note-book size (16)
Table clamp for spring balance (3 required) (18)
Linen fishline (18)
Pencil compass (18)
Spiral spring with weight hanger (22)
Metric mirror scale with metal support (22)
Metric iron weights, slotted, 10 grams to 1000 grams, with holder (22)
Linear expansion apparatus (28)
Steam generator with support, including dipper and thermometer tube fitted with a one-holed rubber stopper (28, 29, 31, 34)
Bunsen burner (28, 29, 31, 34, 64)
(If illuminating gas is not available, use an alcohol Bunsen burner)
Rubber tubing, $\frac{1}{4}$ in. for Bunsen burner, 3 ft. (28, 29, 31, 34, 64)
Thermometer, 110° C., 12 in. long (28, 29, 31, 34)
Vernier caliper, metric, for inside, outside, and depth (28)
Charles'-law tube with dry air and mercury (29)
Lead shot, 1 lb. (31)
Cylindrical graduate, 200 $cm.^3$ (31)
Calorimeter (double-walled with cover preferred) (31, 34)
Steam trap, large test tube with 2-holed stopper (34)
Rubber tubing, $\frac{3}{16}$ in., 3 ft. (34)
Bar magnets, 15 cm., pair (37)

Soft-iron washer, 2.2 cm. diam. (37)
Wood strips, 30 × 1 cm., pair (37)
Magnetic compass, 1 cm. (37)
Iron filings in bag (37)
Voltmeter, triple range, D-C., 0–3, –15, –150 V., commercial type (38, 40, 41)
Simple voltaic cell, with jar, clamp, zinc, copper, carbon, and lead (38)
Sulfuric acid, 1 lb., c. p. (density 1.84) (38)
Hydrochloric acid, 1 lb., c. p. (density 1.19) (38)
Sodium chloride, 1 lb. (common salt) (38)
Copper wire, insulated, #20, 1 lb. (38)
Double connectors with set-screws (2 required) (38)
Dry cells (2 required), (38, 43, 47, 48)
Ammeter, double range, D-C., 0–3, –30 A., portable commercial type (40, 41)
Slide-wire bridge, Wheatstone, 1 meter (40)
Storage battery, 3 cells, 6 volts (40, 41)
Variable rheostat (12 ohm, 4 amp.) (40)
Knife-switch, double-pole, D. T. (40, 43)
Two coils wound with special resistance wire on porcelain tubes; 60 and 120 ohms for 110-volt line current, *or* 4 and 8 ohms for 6-volt battery current (41)
Magnetic compass, 2.5 cm. (43, 48)
Soft-iron core, straight, 12.5 cm. long (43)
Soft-iron U-shaped core (43)
D'Arsonval galvanometer (47, 48)
Induced-current coils about 800 turns of No. 28 wire (2 required) (47)
Magnet, U-shaped (47)
Dissectible model dynamo and motor with A-C. armature and electromagnetic field (48)
Rheostat, 10 ohms (48)
Tuning forks, C–256 and C–512 frequencies (54)
Hydrometer jar, 2 × 12 in. (12, 54)
Glass resonance tube, $1\frac{1}{2}$ × 12 in. (54)
Glass mirror, plane, 5 × 15 cm. (57)
Box of rubber bands, assorted (29, 57)
Protractor (57, 59)
Glass refraction plate, rectangular (59)
Metric rule, bristol board, 15 cm. (59)
Meter-stick supports for optical bench with lens holder, screen holder, and white screen, 10 cm. (60)
Double convex lens, 15 cm. focus, 3.8 cm. diam. (60)
Electric-lamp base with binding posts (without lamp) (60)
Metal shield with wire-screen window to fit above lamp (60)
Glass prism, 60 degrees (64)
Metal screen with narrow slit (64)
Asbestos strips, 1 × 10 cm., set of 4 (64)
Sodium nitrate, 1 oz., c. p. (64)
Lithium chloride, 1 oz., c. p. (64)
Thallium sulfate, 10 g., c. p. (64)
Glass plates, red and blue (64)
Knitting needle (64)
Test tubes, 100 × 13 mm., 1 doz. (64)